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L-Band, Solid State Transmit/Receive Module Phase I Final Report

[Unclassified Title]

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(U) Phase I of a two-phase program to develop solid-state components has been completed successfully. As a result a number of L-band transmitter/receiver (T/R) modules were fabricated by several contractors. The modules were evaluated in a newly constructed, sophisticated, computerized test facility at the Naval Research Laboratory. The modules were engineering models that represented the current state of the art of solid state and concomitant microwave devices and techniques. In most cases stringent specifications and design goals were achieved.

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EXECUTIVE SUMMARY

(U) This section summarizes results of tests conducted by Naval Research Laboratory (NRL) personnel and industrial contractors.

(S) The objective of the two-phase program was to develop a completely solid-state L-band transmitter/receiver module for use in an active-element, phased-array system intended for possible space application.

(U) A module consists of a transmitter, a low-noise RF amplifier, a digitally controlled phase shifter, an isolator, and a T/R switch, housed in a case with integral RF, DC, and logic connectors.

(U) Development of the solid state module was contracted by NRL to three manufacturers: RCA, Contract No. N00014-72-C-0212; Microwave Associates, Contract No. N00014-72-C-0213; and Westinghouse, Contract No. N00014-72-C-0214. To complete Phase I, each contractor had to deliver two working engineering models of a module and a report containing supportive evidence of the module's capabilities.

(U) The six engineering models of the modules received from the three contractors are unsealed units similar in appearance and construction. They are approximately 4.5 in. square overall by 0.75 to 1.4 in. high, and utilize aluminum alloy cases to minimize weight and dissipate heat.

(U) Tests to verify contractors' results were performed at NRL in an extensive test facility configured for this type of task. The evaluation of the receiver channels was accomplished in a CW mode using a Hewlett-Packard (HP) Automatic Network Analyzer, which is computer controlled. The transmitter channels were evaluated in a pulse burst mode using the Scientific-Atlanta Pulsed Measurement System.

Receiver Evaluation

(U) Analysis of the tests performed on the six module receivers indicates that the contractors were able to comply with most of the requirements. All receivers complied with specification for noise figure and gain.

(U) Compliance with the 1-dB bandwidth requirement posed a somewhat different problem. In many cases receivers performed satisfactorily during all phase states for a given supply voltage, but could not maintain compliance with the bandwidth requirement when the voltage was varied.

(U) The differential phase characteristics of all receivers were quite good and met most requirements adequately. Insertion phase lengths as denoted by the electrical equivalent lengths showed unit-to-unit constancy per contractor. It remains to be seen whether the same constancy can be maintained during production runs.

(U) The reliability of the engineering models from all of the contractors was somewhat disappointing. Numerous failures occurred in storage as well as during testing. The proximity of the NRL Test Facility to the sewage disposal plant during the initial stages of the evaluation was considered to be a major factor in the number of failures experienced. The high sulfur content of the air caused considerable erosion of the microcircuitry in these modules, which were not hermetically sealed so that the contents could be inspected visually. Other failures were due to assembly process controls, and some could not be explained. For the next phase of the program the test facility was moved to a new and cleaner environment and the modules may be hermetically sealed, thereby eliminating the cause of many of the failures. The assembly process controls should also be improved, resulting in enhanced reliability.

(U) To ensure the validity of comparisons between receivers, all receiver measurements at NRL were accomplished within the linear portions of the receiver characteristics.

(U) Contractors' results were tabulated from data taken prior to shipping the engineering models to NRL.* It is felt that the tests performed at NRL give a fair evaluation of the receivers; testing was done at room temperature at NRL, whereas the contractors tested over the specified temperature limits.

(U) The results of the NRL module receiver investigation make it difficult to choose the best one from among the contractors' models. Each receiver had both good and bad scores in some respects. The clearest example might be the Westinghouse W-2 receiver. This unit had constant gain independent of supply voltage variations and was the only unit to meet the bandwidth specification. However, its VSWR characteristic was noticeably poor, particularly when compared with other receivers.

(U) Although the NRL investigation was limited in temperature measurements, it should be pointed out that it is probably one of the most thorough ones performed to date on solid state transmitter/receiver modules. Over 1200 pages of computer-generated data (printouts) pertinent to the six module receivers were produced.

Transmitter Evaluation

(U) The six module transmitters suffered from the same lack of reliability as the receivers. Again, failures were sometimes attributed to the high sulfur content of the air in the vicinity. In addition, however, the transistors used in the final amplifiers were multicellular. The cells are individual transistor units that are paralleled on the substrate chip. As many as 32 cells were on some of these chips. As with other first-generation devices, failures were not uncommon as device manufacturers went through their own learning processes and attempted to solve problems of failure mechanisms and other causes of malfunctions. Subsequent device reliability tests have resulted in improved processes, which are expected to provide higher module reliability.

(U) The engineering model transmitters performed remarkably well for first units. In most cases desired output powers were achieved over much if not all of the specified

*For example, Tables 27-29.

bandwidth. Phase response was not always to specification. Phase response of a device is a parameter that varies with temperature, voltage, and external tuned circuits as well as internal tuned circuits. Hard limiting in Class C amplifiers and good heat sinking within and external to the device help to stabilize phase. The problems associated with phase are expected to diminish as device manufacturing techniques and module assembly techniques improve.

Conclusions

(U) Six operating transceiver modules were successfully produced by three contractors. Despite the failures experienced in testing at NRL, it is felt that the objective of Phase I of this program was achieved. It should be reemphasized that all six units were initial engineering models, and therefore some failures were to be expected pending the establishment of process controls and quality assurance measures. The additional 17 Phase II modules should show a marked improvement in reliability.

(S) So far as additional efforts are concerned, module reliability (and associated physics of failure) obviously is a key consideration for space applications. Solid state is still the most promising approach, and compatibility with space environment should be achieved by device passivation and/or hermetically sealing the modules; small size and light weight were achieved.

(U) Reproducibility at tolerable cost remains to be demonstrated and is a direct function of the quantity procured, coupled with good manufacturing and quality control techniques.

L-BAND, SOLID STATE TRANSMIT/RECEIVE MODULE: PHASE I FINAL REPORT
[Unclassified Title]

INTRODUCTION

(S) This report presents a compilation of test results from the Naval Research Laboratory (NRL) and contractors, and is the culmination of Phase I of a two-phase development program for a solid-state component. The objective of the program was to develop a completely solid-state L-band transmitter/receiver module for use in an active phased-array radar. The radar was intended for possible installation on a satellite that would perform ocean surveillance.

(U) A module consists of a transmitter, a low-noise RF amplifier (no converters or IF amplifiers), a digitally controlled, 4-bit, switched-line, diode phase shifter, an isolator (circulator), and a T/R switch, housed in a case with integral RF, DC, and logic connectors.

(U) Contained in this report is a discussion of results pertinent to modules of this type. The results of Phase II will be the subject of a separate report.

(S) For a satellite radar, key requirements for a module of this type are

- High reliability
- Long operating life
- Compatability with space environment
- Small size, low weight
- Reproducible at moderate cost.

In addition, the transmitter output power had to be sufficient and its capability compatible with the receiver noise figure, to make module usage practicable.

(U) With respect to these requirements, it was felt that the candidate that could most likely achieve success was a solid-state electronic unit which, by nature of its composition, inherently possessed most of the necessary properties. Development of the solid state module was initially started in-house at NRL but was later contracted to industrial companies who had less limited development capabilities in the particular area. (Work on experimental RF power amplifiers is continuing at the Electronics Division of NRL.)

Note: Manuscript submitted February 12, 1975.

Three contractors were chosen: Microwave Associates (MA), Burlington, Massachusetts, Contract No. N00014-72-C-0213; RCA, Moorestown, New Jersey, Contract No. N00014-72-C-0212; and Westinghouse, Baltimore, Maryland, Contract No. N00014-72-C-0214. To complete Phase I, each contractor had to deliver two working engineering models of a module and a report containing supportive evidence of the modules' capabilities regarding the electrical and mechanical characteristics specified by NRL (see Appendix A).

(S) It should be pointed out that the electrical specifications, when written, were intended to be practical and realizable from the aspect of a generalized transmitter/receiver module. The specifications did embody the requirements of a Satellite Ocean Surveillance System resulting from the classified space program No. 749 system studies. It was also intended that the specifications would spearhead a valuable probe into the present state of the art of solid state and concomitant microwave devices and techniques, to determine just what could be accomplished at this point in time.

(U) The first phase of the program was preliminary in that the continuation of the program was dependent on the achieved performance of the engineering models. By carefully monitoring contractors' progress, it was determined that Phase II was justified, and hence contracts to the same three companies were subsequently awarded. To complete Phase II each contractor must deliver several preproduction protype models of a module. These will undergo thorough evaluation by NRL.

(U) The purpose of the work done by NRL with respect to the modules was manifold. Initially, it was to test and evaluate the modules both to confirm and verify contractors' test results. As an adjunct, it was to extend the test frequency limits beyond those required by specification as an aid in determining more completely the capabilities of the present modules and requirements for future modules. A longer term goal was to set up a test facility of reasonable versatility that could be used to assist NRL and other similar agencies to test and evaluate future modules operating anywhere in the L- through X-band regions. Work on this goal is a continuing process that will be maintained after this program is completed.

(U) The six engineering models of the modules received from the three contractors are similar in appearance and general construction. All are unsealed units approximately 4.5 in. square overall by 0.75 to 1.4 in. high with aluminum alloy cases to minimize weight and dissipate heat. The MA has a plexiglass cover plate on one surface so that the module interior can be observed without removing a metallic cover. All use chip-type transistors and diodes in conjunction with chip-type capacitors for most circuits. Subminiature feedthrough capacitors are used to carry buses through shielding partitions, and subminiature storage capacitors are used to maintain voltage levels while supplying high pulse currents to transistor collectors in the output stage of the transmitters.

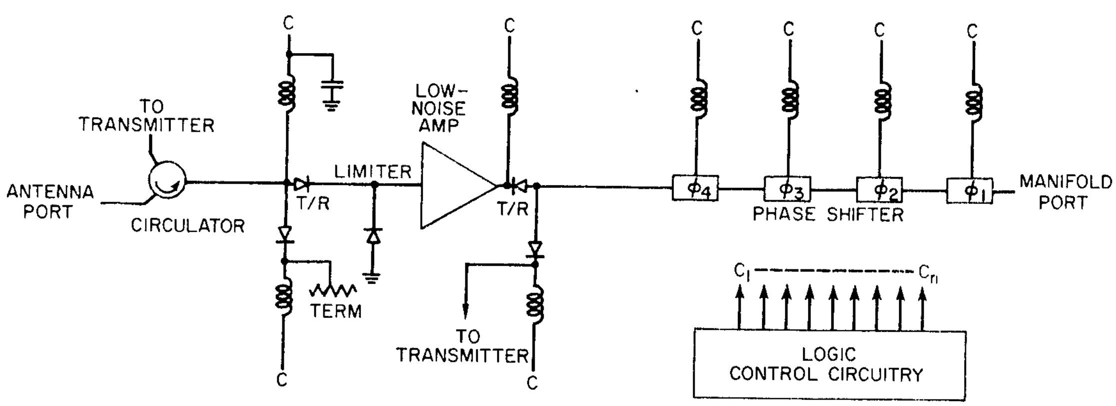
(U) All circuits were constructed on alumina (Al_2O_3) substrates which were variously metalized or plated, e.g., chrome-gold metalized with gold-plated aluminum carriers (Microwave Associates), molybdenum, nickel and gold-plated carriers (RCA), and tantalum and gold-film metalized carriers (Westinghouse).

(S) A secondary purpose of the program was to determine the state of the art of solid state "high-power" transmitter design and to stimulate further activity by private industry in this field. The emphasis was not so much on how far a device could be "pushed" to produce more RF output power over a given band of frequencies but was instead directed toward high reliability and reproducibility of devices and subsequent transmitter units. Availability of inexpensive, reliable solid state transmitters would provide the radar designer with a building block usable directly in satellite phased-array radars or, by RF power combination, usable in more conventional satellite dish-type radars. In either case, the use of modular means for obtaining total radar output power allows radar end-of-life to be approached with graceful degradation of power rather than abrupt termination of output.

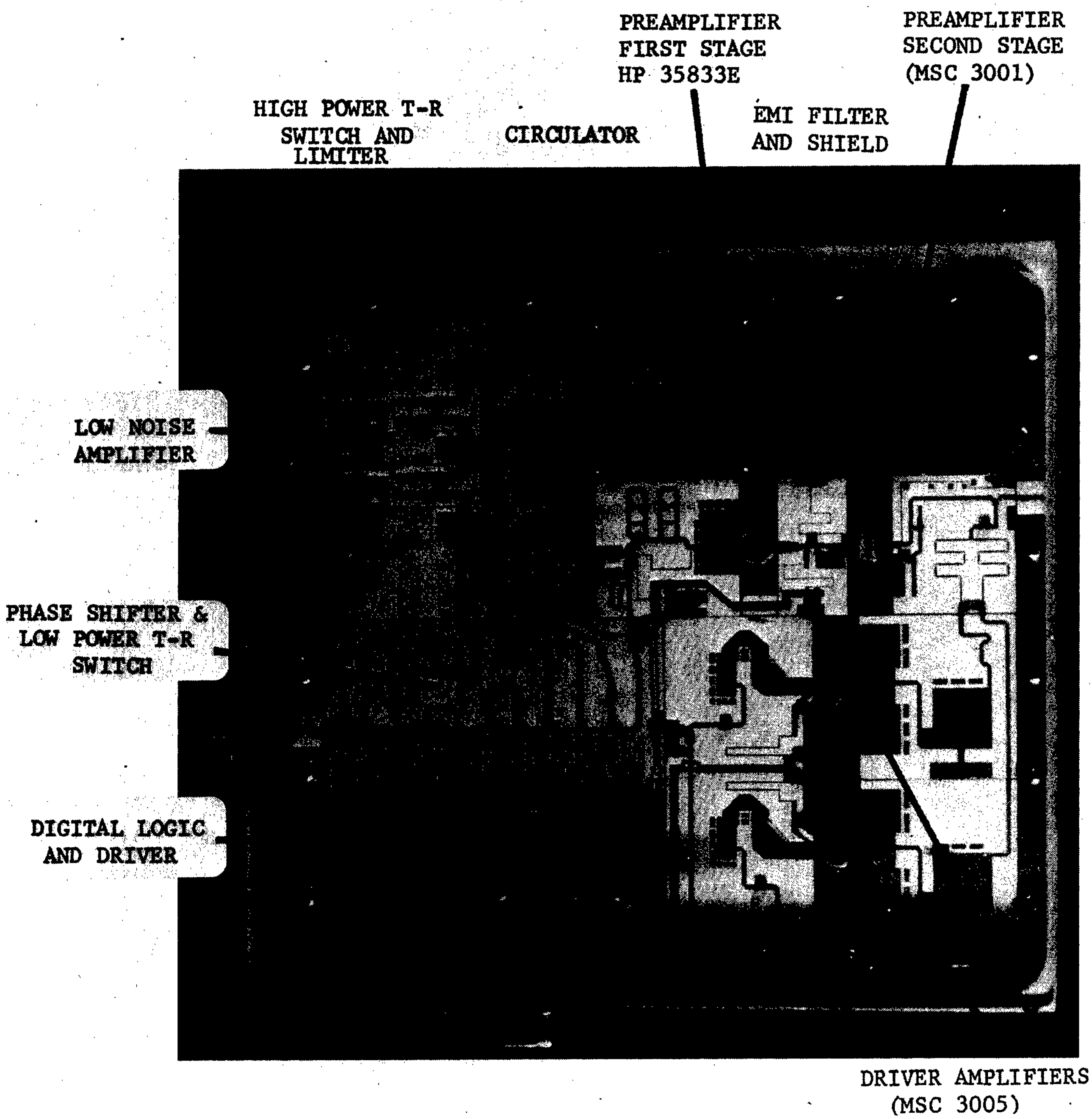
RECEIVERS

(U) The receiver will be considered as a set of components that start with the antenna port. It includes the circulator, T/R switch, limiter, low-noise amplifier, phase shifter, digital control, and sundry ancillary circuitry.

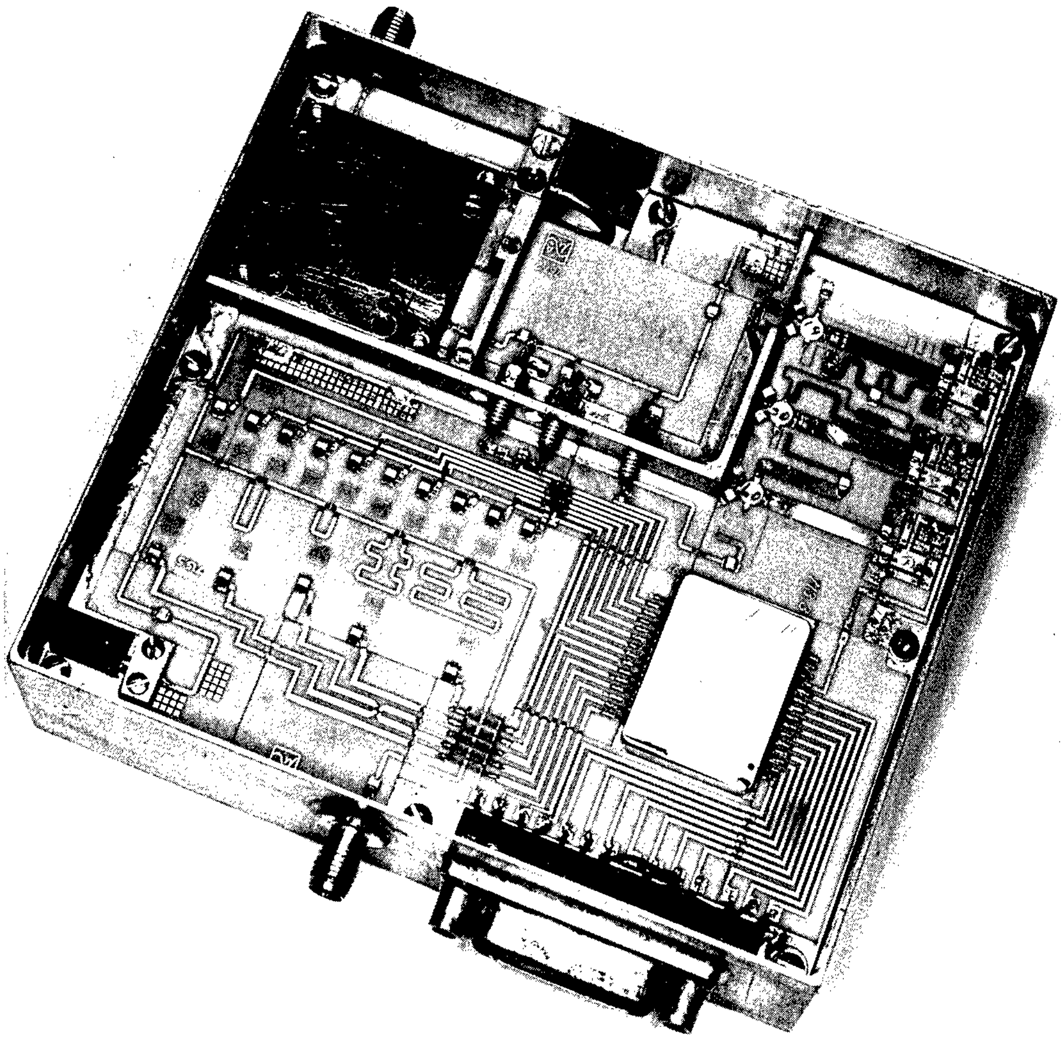
(U) The receivers were all of the general form shown in Fig. 1. Signal flow from the antenna port was through a circulator, a T/R switch, and limiter to a low-noise amplifier. After amplification the signal passed through a second T/R switch and a 4-bit phase shifter capable of 16 phase states in 22.5-degree increments, and exited from the manifold port. The low-noise amplifiers apparently had excellent noise figures but contributions from the circulator, T/R switch diodes, limiter diode, and associated circuitry in each case degraded the noise figure by about 1 dB at room temperature. Figures 2, 3, and 4 are photographs of the receiver sides of the modules. Since the modules are similar, the callouts on Fig. 2 are typical for all. Some design details for the low-noise amplifiers, gleaned from contractor reports, follow.



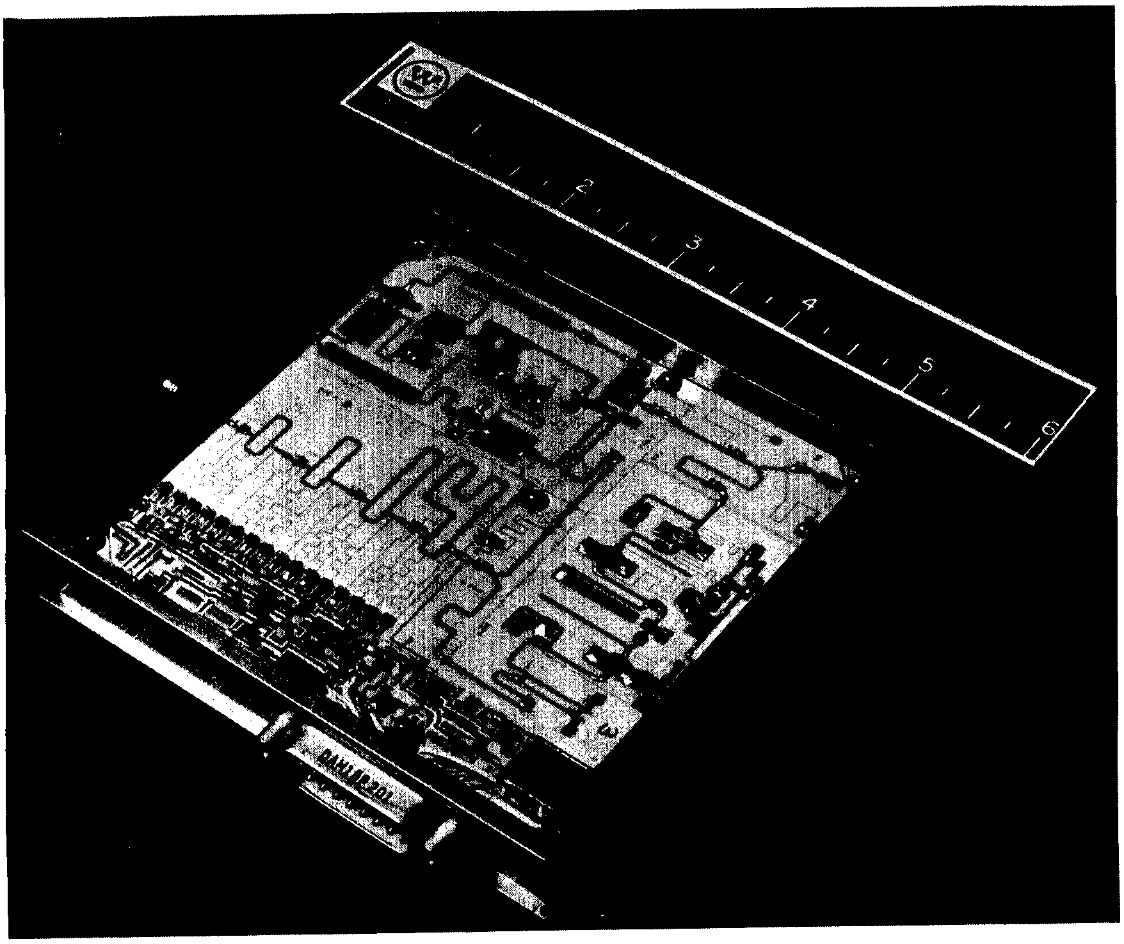
(U) Fig. 1 — General receiver circuit



(U) Fig. 2 — RCA receiver



(U) Fig. 3 — MA receiver



(U) Fig. 4 — Westinghouse receiver

(U) The Microwave Associates' low-noise amplifier was constructed on a 1.0 in. by 2.0 in. by 0.020-in. alumina substrate and was designed using a computerized optimization program. The amplifier is composed of three stages operated in the common-emitter configuration. The emitter circuits are provided with 100-ohm resistances to ground and are bypassed with two 100-pF capacitors. The general structure of the base and collector circuits is a series line followed by a shunt stub terminated by a 100-pF capacitor. In all cases, the capacitor shorted stub is nearest the transistor. The input, output, and interstage coupling capacitors (which are also 100-pF) are between the series lines.

(U) The noise figure requirement necessitated the use of a transistor with exceptional characteristics; i.e., a first-stage transistor noise figure of 2.2 dB was needed to achieve an amplifier noise figure of 2.7 dB. The overall noise figure was equal to the sum of the amplifier noise figure and the insertion loss of the circulator, front-end protection switch, and limiter circuits. It was, therefore, very important to control the insertion loss of all devices preceding the low-noise amplifier.

(U) The first-stage RF transistor requirement was filled by an Avantek Model AT640AS1, the second and third stages by transistors of the same manufacturer, Models AT50A and AT50, respectively. The important characteristics are listed in Table 1.

(U) Table 1
Avantek Transistor Characteristics

Stage	Model	G_{max} (I_c = 15 mA) (dB)	Noise Figure (I_c = 5 mA) (dB)	I_c in Actual Operation (mA)
1	AT640AS1	15	2.2	3
2	AT50A	14	2.5	10
3	AT50	14	3.0	10

(U) A temperature compensation circuit was used to ensure that a uniform collector current is present in each stage of the amplifier. To allow the amplifier collector currents to vary because of the temperature environment would produce gain variations in excess of the specification limit.

(U) The RCA low-noise amplifier design consists of three stages in cascade using bipolar packaged transistors. The amplifier is of the hybrid integrated circuit form of construction.

(U) Three Fairchild transistors were used. The first stage, an MT 4000, was designed for low-noise operation. The second and final stages, a 2N5261 and an MT 4415, provided the necessary gain at complementary compression points. The compression point of the second and final stage was designed to be 1 to 2 dB higher than the gain of the stage ahead of it. The overall gain of the amplifier was larger than the required receiver gain by the amount of the front-end losses, the losses of the phase shifter and the low-power T/R switch. The noise figure requirement of the low-noise amplifier was designed to be lower than the receiver requirement by the amount of the losses of the module's antenna T/R switch limiter and circulator combined. The low-noise amplifier requirements include

design for low-power consumption. The listing below is a summary of the low-noise amplifier requirements as interpreted by RCA.

(S)	Noise figure	4 dB - 1 dB loss = 3 dB (max)
	Gain	25 dB + (1 dB + 3 dB) = 29 dB (min)
	Compression point	-25 dBm - 1 dB = -26 dBm
	Operating voltage	10 V
	Operating current at ambient temperature	20 ma
	Phase linearity	±1° per 30 MHz (specification requires 20 MHz)
	Gain linearity	±.5 dB per 30 MHz (specification requires 20 MHz)

(U) The design of the amplifier stages accomodated the manufacturer's variations in transistor parameters by providing adjustable line length in the microstrip circuitry. The RF circuit design was based on Smith chart solutions of the input, output, and interstage distributed transmission line network. With the current variations in device parameters, these solutions were done for the worst-case characteristics to determine the variation of line length. A short circuit adjusted the noise figure over the operating frequency. Another short circuit and the position of a blocking capacitor adjusted the output impedance match over the frequency band. Two blocking capacitors adjusted the interstage impedance match, the gain, and the gain frequency tilt.

(U) The amplifier uses an all-distributed RF printed circuit for highest reproducibility. The blocking capacitors are the only lumped components in the signal path; no lumped elements are used as resonant circuit elements.

(U) The bias circuits include resistive voltage-dividing networks, incorporating some temperature and supply voltage stabilization. This stabilization could be increased with additional current stabilization at the cost of amplifier efficiency.

(U) Two types of each of the transistors for the low-noise amplifier were evaluated. One of the prototype amplifiers was subjected to temperature cycling and 168 hr of burn-in at elevated temperature, as well as vibration and shock testing without observable degradation in the amplifier's performance.

(U) The low-noise amplifier used in the Westinghouse module receive chain is a thick-film, 3-stage, single-tuned amplifier with integrated gain and phase trimming networks. The transistors used in this amplifier are supplied by Nippon Electric Corporation. The first stage is a 2SC1268, with a 2.1-dB maximum noise figure at 1.3 GHz. The second and third stages are both 2SC-1336s. With this first-stage noise figure, Westinghouse measured an overall gain of approximately 34 dB at a 2.5-dB noise figure. At the beginning of this program, Westinghouse decided that the only devices available that would provide the required noise performance at 1.3 GHz were the Nippon transistors. The Fairchild MT 4000, which appeared from preliminary data to be adequate, was plagued with early production-line problems resulting in a minimum guaranteed noise figure of

only 2.3 dB. Westinghouse feels that these problems have now been resolved, and both Nippon and Fairchild will be able to provide low-noise transistors for future modules.

(U) Because of the percent bandwidth specification, Westinghouse felt that single-tuned transmission-line stub and line networks were more than adequate for matching each of the three stages in the amplifier. The design philosophy was to match the first stage for optimum noise performance while matching the second and third stages for maximum gain. The addition of a 4-dB attenuator between the second and third stages was also of fundamental importance to the design. This attenuator was used to reduce the gain to a desired level and to provide sufficient isolation between stages to allow for noninteractive, stagger tuning of the second and third stages. In addition, the dynamic performance of the third stage was improved by 4 dB. The additional isolation between stages reduced the gain and phase sensitivity of the entire amplifier to changes in load VSWR resulting from the various phase-shifter bit configurations.

(U) A positive supply bias configuration was employed because the advantages of not having to float the emitters of each transistor far outweighed the disadvantage of increased gain and phase sensitivity of the amplifier to bias variations. By providing some very simple current regulation (which also provided a convenient means of gating the amplifier bias), Westinghouse claimed that the sensitivity of the amplifier to bias variations was an order of magnitude better than specifications.

(U) The phase trimmer employed in the amplifier is a simple trombone section of line with a sliding capacitor, and it provides up to 30 degrees of phase trimming. The gain trimmer consists of a semilumped branch-line quadrature hybrid with terminations capable of being trimmed. The quad is inserted in the signal path so that two adjacent parts of the hybrid are the input and output ports. The intent is that with the other two ports terminated in 50 ohms the hybrid will exhibit more than 20-dB insertion loss, but as the terminations are trimmed to higher and higher values more signal will be reflected back from the mismatched terminations to the output port. In the limiting case where the terminating resistors are cut open, the insertion loss of the quad between the adjacent input and output ports is supposed to be less than 1 dB. The convenient feature of this type of gain trimmer is that both resistors trim in the same direction, as opposed to a Pi or Tee attenuator where two resistors are raised in value while one must be decreased in value. The disadvantage of a branch-line quadrature hybrid for this application is that it is inherently narrowband.

Receiver Measurements

Instrumentation

(U) Test instrumentation for obtaining most module data at NRL consisted mainly of two major items: A Hewlett-Packard (HP) Automatic Network Analyzer Model 8542A and a Scientific-Atlanta (S/A) Pulsed Microwave Measurement System for receiver and transmitter measurements, respectively.

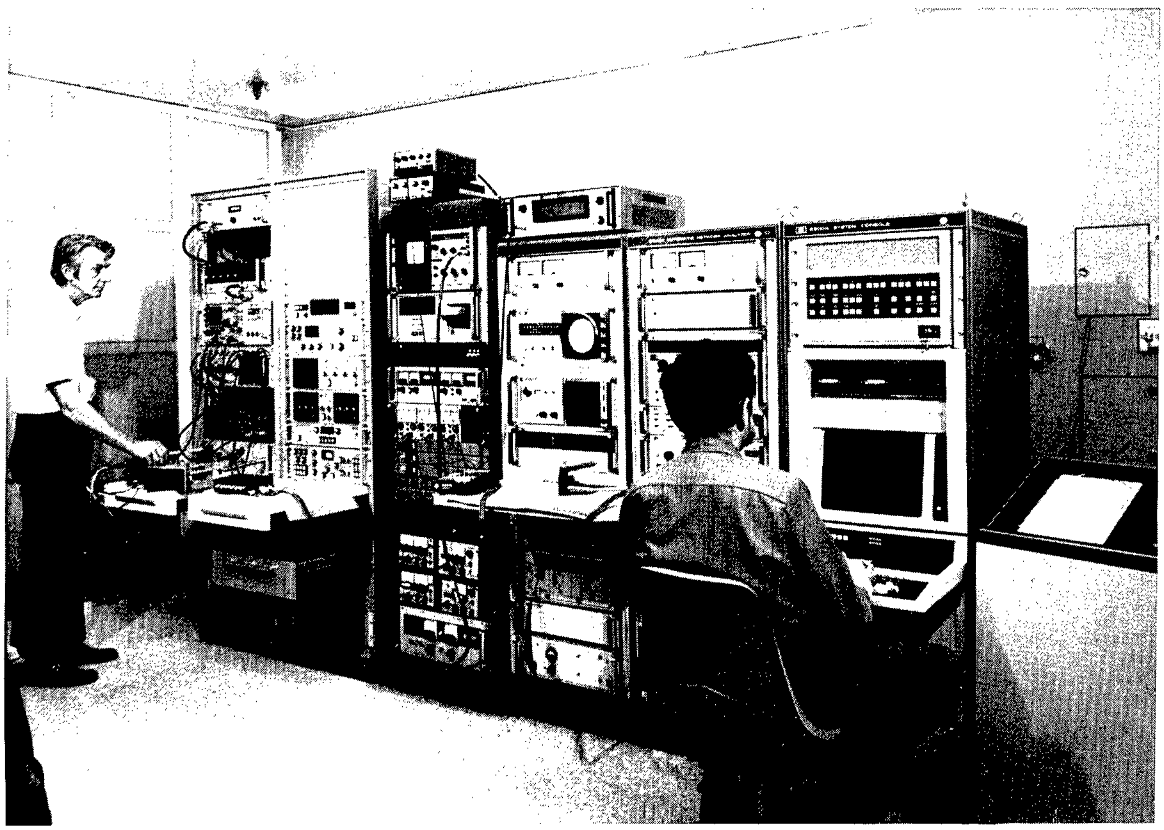
(U) Figure 5 shows the test equipment setup as it was when located in building 29 at NRL. From right to left can be seen the Versatek printer which produces paper printouts of graphics (text and plots) upon command by the HP computer; the three racks comprising the HP Automatic Network Analyzer; a separate rack containing power supplies for modules, laboratory-built digital equipment, and digital voltmeters for accurate voltage monitoring; and the two racks comprising the S/A Pulsed Microwave Measurement System. The operator on the right is seated at the keyboard through which instructions can be entered into the computer. The dark square in front of the operator contains a CRT on which data can be displayed as alphanumerics (listings) or graphs (rectangular or polar plots). Any material displayed on the CRT may be produced as hard copy by the Versatek printer at the will of the operator or by programmed computer command. Directly above the display is a three-deck magnetic tape cassette unit which is computer controlled when on line, and manually operated when off line. The computer itself is uppermost in the rack. The other two racks of the HP set contain various RF signal generators and control units, power supplies, attenuators, and displays. The entire set of test equipment, when fully operable, is intended to be a sophisticated facility dedicated to testing transmitter/receiver modules under pulsed or continuous wave (CW) RF conditions.

(U) In the midst of testing the engineering model modules it became necessary to move to new quarters in building 208 at NRL. The equipment was installed temporarily in a laboratory where testing of the modules proceeded. During that time the next location for the test equipment was prepared so that the test facility could be in a laboratory capable of becoming a high-level clean room.

(U) Because of test equipment operational difficulties and sporadic module failures the extent of the module investigation was somewhat more limited than desired. However, enough data were obtained so that a good determination of the modules' capabilities was formed.

(U) Those receiver measurements that produced phase and amplitude data simultaneously and at many frequencies were made with the HP Automatic Network Analyzer using CW RF signals. This unit provides a programmable signal source to excite the device under test, a network analyzer to measure phase and amplitude, a programmable test set to select the proper signals to determine device parameters, and a stored-program computer and peripherals. Systematic errors within the analyzer are determined by means of calibration programs and by measuring precision loads, shorts, opens, and air lines and comparing measured data with the known characteristics of these devices. Error coefficients at each frequency are determined mathematically and stored for later use to correct measured data on the unknown. Sources of error such as source and load mismatch, coupler directivity, crosstalk, and gain differences between the two channels of the analyzer are thereby considerably reduced.

(U) Programs are loaded into the computer by means of magnetic tape cassette. After the calibration program is entered, a CRT display requests RF-frequency information from the operator. As this is entered from a keyboard the signal source is automatically programmed. Introduction of the precision loads, etc. is requested and as each is inserted into the test channel a measurement is made and the data stored. This constitutes



(U) Fig. 5 — Microwave Integrated Circuit Module Test Facility

calibration. Upon completion, the calibration data can be written on a magnetic tape or simply left stored in the computer.

(U) The calibration procedure as described consists of utilizing single data points at the many frequencies comprising the operating band. Subsequent updating of the software permits taking multiple data points and utilizing averaging in order to reduce the effects of noise in the system and improve the accuracy of calibration. To validate the calibration, the test-channel connections are loosened, moved about and tightened, and then another measurement is made. The listing of data thus obtained shows the differences between the measured parameters and the calibration data taken from the same electrical/physical setup which in all cases should be almost zero. Differences much greater than zero usually indicate that a fault (bent or loose connection, damaged component) existed during calibration, in which case the calibration must be redone.

(U) The measurement program is now loaded into the computer and the module to be tested is inserted into the test channel. Direct current is applied to the module, a desired phase state is entered into the module, a set of measurements is made, and the data are recorded on magnetic tape in the form of scattering (S) parameters which characterize the high-frequency performance of the receiver.

(S) Forty-one frequencies spaced 5 MHz apart were used to cover an arbitrary bandwidth of 1150 to 1350 MHz (F_{LL} to F_{HH}) which encompassed the specified band, 1187.5 to 1312.5 MHz (F_L to F_H).* For each module at each frequency, phase, transmission gain, and VSWR measurements were made for each of 16 phase states from 0 degrees to 337.5 degrees (22.5-degree steps). Similar measurements were made at nominal DC input voltages and at ±2% about the nominal.

Data Processing

(U) The data processing program used to generate plots and listings from the receiver data required the complex values of the S parameters as obtained from the HP Automatic Network Analyzer. These data, as recorded on magnetic tape, consisted of a sequence of records, each containing the frequency and the S parameter values measured at that frequency. All records that represented the results of a particular set of test conditions such as voltage, temperature, phase state, etc. were grouped in a file. Within a file the data are ordered as a monotonically increasing function of frequency and are equispaced. This fact was used to convert phase measurements from a modulo 360 representation to a continuous function. In addition to the data, each file contains a tape identifier record which was not used during processing but was printed at the top of an output page of a plot or listing as a heading.

(U) Since the data were taken over a broader band then originally specified, information such as the band edges and other specification limits was entered from the keyboard at

*(S) Where the exact frequencies of 1187.5 and 1312.5 MHz could not be obtained, nearby frequencies were substituted, e.g., 1190 and 1310 MHz. F_L and F_H represent the exact and substitute frequencies. F_C denotes 1250 MHz, the band center.

processing time. All data from the tape could be displayed but only data lying within the band was used for any computations that might affect the specification limits.

(U) All phase data were related to the "reference file," which is the file containing the "zero phase bit" data. Therefore, all phase data had the reference file phase data subtracted from it before being processed.

(U) Since all other phase data were processed relative to the reference file, special processing was needed for this file. First, rms best fit polynomials of degrees one and two were generated to approximate the phase vs frequency data. The slope of the first-degree polynomial was used to generate the equivalent airline length of the module insertion phase, and the offset was given by the y-intercept modulo 360. The two polynomials were assumed to be ideal: the linear and quadratic phase errors are the differences between the polynomials and the actual data.

(U) After the reference file was processed, all the files including the reference file were processed as comparison files. The phase data were corrected to be relative to the reference file, and the phase state of the module was taken to be that of the relative phase at the lower edge of the band, rounded to the nearest 22.5 degrees. Based on this value, an ideal relative phase vs frequency curve was generated using

$$\theta_s = \left(\frac{\text{Phase state}}{\text{Lower frequency band edge}}\ \text{frequency}\right).$$

The curve was used to compute the differential phase error. The differential slope is defined as the slope of the rms best-fit straight line used to approximate the differential phase error over a given instantaneous band beginning at the listed frequency.

Test Results

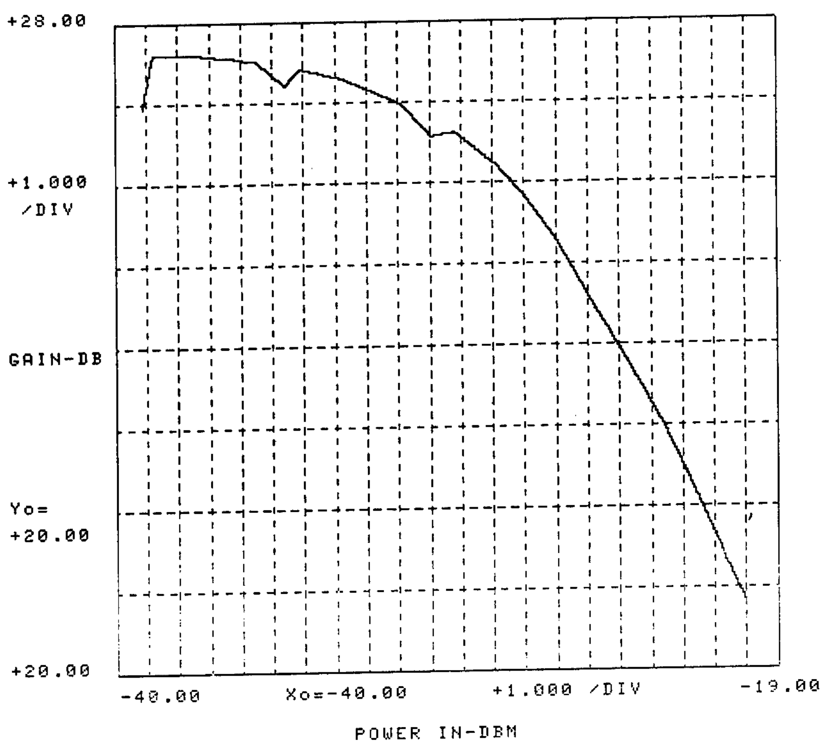
Receiver Dynamic Range

(U) The RF input level used for testing the receivers was −35 dBm. (The actual output of the HP analyzer was $-35^{+1.6}_{-0}$ dBm, depending on frequency.) This level was chosen for two reasons. First, it was felt that the specified input of −25 dBm, at which the compression could be 1 dB, meant that compression would start well before that point and approach the 1-dB point gradually. It was desired that the receiver be operating in the linear portion of its transfer characteristic during testing. Second, the low signal limit for the HP analyzer below which noise would be excessive was in the order of −40 dBm. With the signal level variation expected with frequency (from the analyzer), −35 dBm appeared to be a good compromise and noise would not be present at a high enough level to affect measurement accuracy.

(S) The validity of the choice can be demonstrated by examining in some detail the results of dynamic range tests. Figures 6, 7, and 8 show the effects on receiver gain of varying the input level while operating at a constant frequency. (The periodic dips in

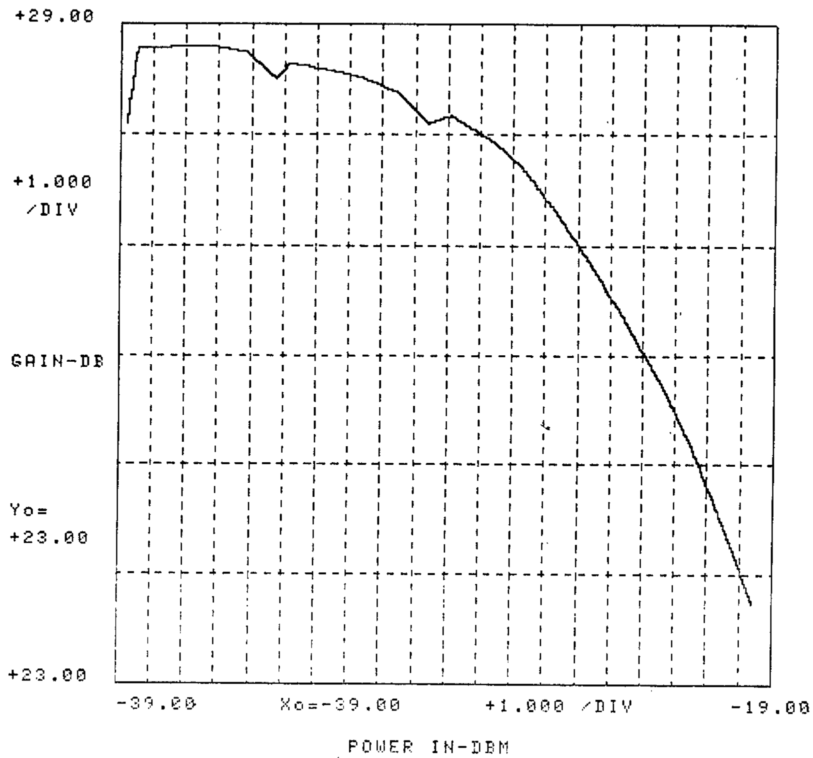
the curves appear to be due to some sort of errors that occur as the variable attenuator is moved through its range.) It can be seen that the receiver gain in each case is down about 0.1 dB at the -35 dBm input level. The RCA-2 receiver dynamic range was first tested at NRL manually in a bench setup. The results compared with those from RCA's report are shown in Table 2. The plots shown in Figs. 6, 7, and 8 were generated from data taken at a later date. These data came from tests run using the HP Automatic Network Analyzer. For these tests an FXR* variable attenuator was used to control the input level to the RCA-2 receiver in 1-dB steps, from -40 dBm to -20 dBm. At each step data were taken at 20-MHz intervals over the range of 1150 to 1350 MHz. A program was written to reduce the data and produce a plot (similar to the three presented here), for each frequency, of receiver gain vs RF input level. From these plots, the 1-dB compression points were picked off and plotted as shown in Fig. 9. Also shown are plots of receiver gain during the 1-dB compression and with -35 dBm input levels as used for the automatic tests to be discussed later in this report.

(U) To summarize, it is felt that to make sure receivers are tested within the bounds of their linear characteristics, the test input level should be well below the specified 1-dB compression point. The rule of thumb applied here was to use a test signal 10 dB below that point.

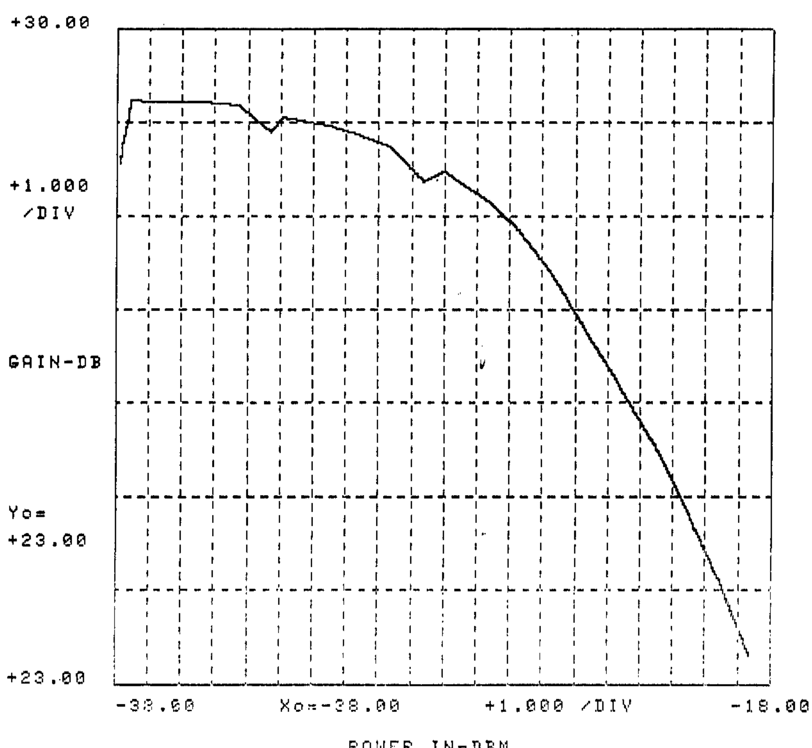


(S) Fig. 6 — Gain vs input power, frequency = 1190 MHz

*Microlab/FXR, 10 Microlab Road, Livingston, N.J.



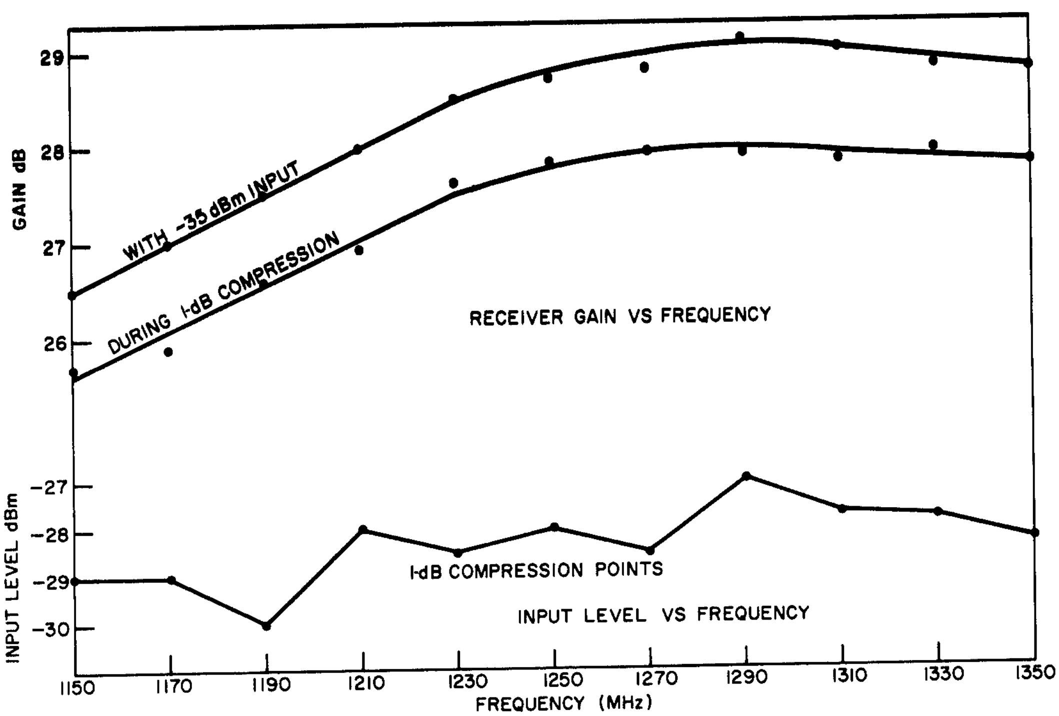
(S) Fig. 7 — Gain vs input power, frequency = 1250 MHz



(S) Fig. 8 — Gain vs input power, frequency = 1310 MHz

(S) Table 2
Input Levels for 1-dB Compression

Frequency (MHz)	RCA-1 (dBm)		RCA-2 (dBm)	
	RCA	NRL	RCA	NRL
1190	-24	-26.6	-23	-25.5
1250	-24	-27.3	-24.5	-28.1
1310	-24.5	-27.0	-23.5	-28.0



(U) Fig. 9 — Receiver gain and input level vs frequency, RCA-2

(U) The RCA-1 module receiver evidently suffered the same problem as the RCA-2 receiver, but to a slightly lesser degree. Its compression points are listed in Table 2. The NRL test data differ from RCA's for this module just as they did for the RCA-2 receiver.

(U) In comparison, the results of manual dynamic range tests on Westinghouse and Microwave Associates receivers are shown in Tables 3 and 4. As is evident from Table 4, the NRL data for the Westinghouse receivers compare favorably with those of the contractor. Both receivers operated well within the specification values.

(S) Table 3
Input Levels for 1-dB Compression, W-1, W-2

Frequency (MHz)	W-1		W-2	
	Westinghouse (dBm)	NRL (dBm)	Westinghouse (dBm)	NRL (dBm)
1190	-21	-20.8	-24	-23.5
1250	-18, -19	-18.5	-20	-19.7
1310	-18	-17	-19	-18.5

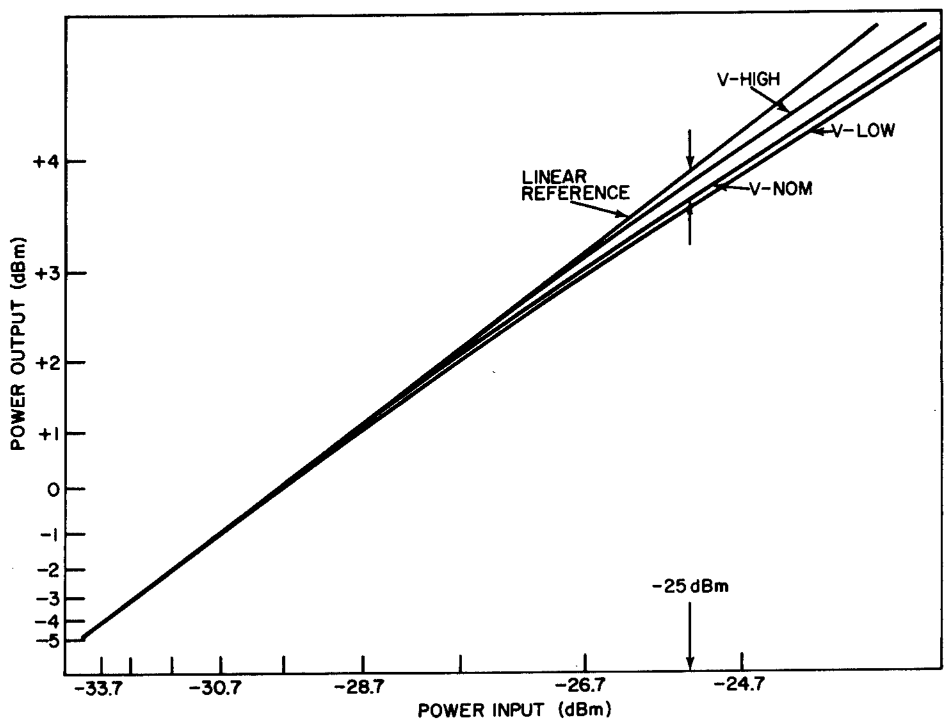
(S) Table 4
Input Levels for 1-dB Compression, MA-1, MA-2

Frequency (MHz)	MA-1		MA-2	
	MA (dBm)	NRL (dBm)	MA (dBm)	NRL (dBm)
1190	—	-20	—	-21
1250	—	-21	—	-21
1310	—	-22	—	-21.5

(U) With respect to the Microwave Associates receivers, NRL measurements showed compliance to specifications. The contractor did not submit values to indicate receiver compression points. Instead, the contractor supplied plots of receiver gain vs input levels that showed that the receiver gain in each case was down less than 0.5 dB at -25 dBm input levels.

(U) Microwave Associates reported that their receiver measurements were made with an input level of -25 dBm. By the rule of thumb discussed previously, a receiver should be compressing the signal to some degree with that input level. Figure 10 is the plot submitted by Microwave Associates to show compliance of their module 1 to specifications for dynamic range. The center curve of three is compared with a straight line (extrapolation presumably of the linear portion of the input/output receiver characteristic) under conditions of nominal power supply voltages, center frequency, and room

temperature. The distance between the two arrows along the -25 dBm power input line is the one of interest and appears to be several tenths of a decibel. While not a great deal, it is not know what effect the compression has on the phase response of the receiver vs the uncompressed phase response. How the VSWR would be affected would probably depend on where within the amplifier limiting was taking place. It is estimated that with the three-stage amplifier used, the input to the first stage would be almost completely unaffected by slight limiting in the third or even the second stage.



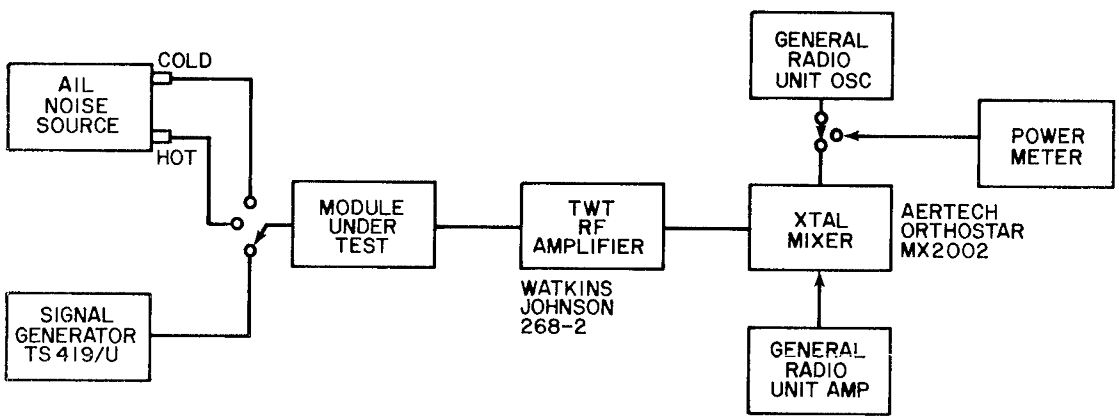
(U) Fig. 10 — MA-1 receiver dynamic range

(U) The Westinghouse receivers were tested with -30 dBm power inputs which are nearly 10 dB lower than the module compression points (see Table 3). It would appear that the receiver compression with those inputs should have been minimal or nonexistent. All other things being equal, measurements at these levels should have been valid.

(U) RCA made their measurements by first calibrating the measuring equipment at approximately -5 dBm and then inserting a precalibrated, 30-dB, fixed attenuator in front of the receiver. Data taken this way, while improving the quality of the gain measurements with respect to linear receiver operation, allow some error due to the attenuator and the accuracy of its calibration. In addition, since a HP Automatic Network Analyzer was used for making the measurements, the VSWR measurements made on the analyzer were effectively invalidated because of the 30-dB attenuator at the input to the receiver.

Noise Figure Measurements

(U) Measurements of receiver noise figures were made at NRL to confirm those made by the contractors. These were done by the classical method using the setup illustrated in Fig. 11. The module antenna port is first connected to the signal generator which supplies a -80 dBm RF level at the desired frequency. The frequency of the unit oscillator is adjusted by obtaining maximum response on the unit amplifier indicator meter, which is calibrated in decibels of second detector current. The unit amplifier is a narrowband, 30-MHz center-frequency device with a detector and a meter calibrated to 10 dB in 0.2-dB steps. An integral 70-dB variable attenuator is furnished with this amplifier.



(U) Fig. 11 — NRL noise figure measuring setup

(U) The module input is then connected to the hot terminal of the noise source and the unit amplifier attenuator is adjusted for a convenient reading on the meter. The cold terminal of the noise source is then used as an input to the module and a second meter reading is taken. The difference between the two readings results in a "Y" factor from which the noise figure is computed:*

$$\text{N.F.} = 10 \log_{10} \left(0.734 + \frac{1.02}{Y-1}\right).$$

(S) The specified maximum allowable noise figure is 4.0 dB over the band, measured at the antenna port of the module. The NRL measured values for noise figure taken at room temperature and zero degrees phase state are listed vs those taken by the three contractors in Tables 5, 6, and 7. As far as is known, Westinghouse made their

*See Appendix B for derivation.

measurements using automatic noise measuring equipment verified and corrected by the hot-cold method, Microwave Associates used the noise generator method, and RCA used automatic measuring equipment. The NRL measurements correlated with those of the contractors within several tenths of a decibel in all cases. The two Westinghouse receivers clearly had superior noise figures. The RCA-2 receiver (by NRL's measurements) appeared next best in this respect. All other receivers could be lumped in one category. Although some of the NRL data show values greater than 4.0 dB, it is felt that to place the out-of-specification label on the receivers would be improper. It is extremely difficult to improve measurement correlation beyond that obtained, when making noise figure measurements by different methods in different places, at different times, and by different operators.

(S) Table 5
Noise Figure vs Frequency, W-1, W-2

Frequency (MHz)	Noise Figure for W-1 (dBm)		Noise Figure for W-2 (dBm)	
	NRL	Westinghouse	NRL	Westinghouse
1210	3.11	3.20	3.26	3.25
1230	3.26	3.17	3.26	3.20
1250	3.14	3.17	3.15	3.21
1270	3.23	3.23	3.33	3.28
1290	3.41	3.26	3.38	3.32
1310	3.45	3.32	3.58	3.39

(S) Table 6
Noise Figure vs Frequency, MA-1, MA-2

Frequency (MHz)	Noise Figure for MA-1 (dBm)		Noise Figure for MA-2 (dBm)	
	NRL	MA	NRL	MA
1170	3.98	3.8	3.98	3.8
1190	3.98	3.73	3.85	3.73
1210	3.79	3.75	3.94	3.79
1230	3.79	3.71	3.88	3.75
1250	3.61	3.67	3.98	3.76
1270	3.61	3.78	3.94	3.82
1290	3.79	3.77	3.98	3.82
1310	3.83	3.81	4.11	3.85
1320	3.98	3.79	4.07	3.85

(S) Table 7
Noise Figure vs Frequency, RCA-1, RCA-2

Frequency (MHz)	Noise Figure for RCA-1 (dBm)		Noise Figure for RCA-2 (dBm)	
	NRL	RCA-1	NRL	RCA-2
1150	3.90	—*	3.67	—
1160	3.85	—	3.67	—
1170	3.85	—	3.61	—
1180	3.81	—	3.58	—
1190	3.94	3.80	3.50	3.85
1200	3.94	—	3.58	—
1210	3.94	—	3.79	—
1220	3.98	—	3.76	—
1230	4.04	—	3.55	—
1240	3.94	—	3.55	—
1250	4.04	3.90	3.58	3.85
1260	4.04	—	3.58	—
1270	4.04	—	3.67	—
1280	3.94	—	3.55	—
1290	4.08	—	3.58	—
1300	4.00	—	3.41	—
1310	4.04	3.90	3.55	3.80
1320	4.00	—	3.58	—
1330	3.85	—	3.50	—
1340	3.85	—	3.41	—
1350	4.08	—	3.37	—

*Dashes indicate no data taken.

Automatic Testing

(U) The results of the HP Automatic Network Analyzer receiver measurements taken at room temperature are presented in computer-generated printouts of plots and tabulations of computed data. Since the amount of data collected for each module is voluminous, a sampling of typical printouts and those printouts summarizing salient features of receiver behavior will be included here. Headings and titles for the data will be explained by examining a group of tabulations and plots associated with the measurements made on the RCA-1 module. These will serve as examples for the discussions which follow. Note that the power supply voltages for the module were 2% below nominal, which would be expected to produce the lowest gain if gain is voltage dependent.

(U) In Fig. 12, which shows the insertion phase data for the Specified Band, the phase-equivalent airline is the insertion phase as described by a best-fit line to a plot of module insertion phase vs frequency. This printout indicates that the module insertion phase is equivalent to a 148.09-cm airline when the module phase shifter is set to the 0-degree phase state. This value of airline is computed by finding the best-fit linear equivalent to the curve of insertion phase vs frequency over the band and obtained from measured data for this module and is, of course, frequency dependent. The 11.89-degree offset is a frequency-independent term obtained by extrapolating the linear equivalent to zero frequency and subtracting out $n\pi$ degrees. The rms error stated in Fig. 12 is the insertion phase error, the deviation from the linear equivalent, and is derived from the data shown in column 2, Fig. 13. Note that all computations are made over the specified band only. The peak insertion phase error is 1.67 degrees and it occurs at 1305 GHz.

(U) The quadratic degrees (Fig. 13) are determined by generating a synthetic curve of second degree which best fits the insertion phase curve. Values of coefficients A_0, A_1, and A_2 are listed in Fig. 12. The listing in Fig. 13 is the difference between the synthetic curve and the measured data. The cyclical nature of the listed values implies that higher order differences are also present.

(U) Figure 14 is a printout listing the differential phase rms error to be 2.90 degrees for all 16 phase states with a concomitant peak error of -7.18 degrees, both well within specification.

(U) The spread of differential phase error vs frequency is shown in Fig. 15. Each vertical line represents the maximum and minimum excursions of the phase error magnitude as the module phase shifter is moved through the 16 possible states. By definition, the differential phase error is the difference between the desired value of differential phase and that value computed from measured data. The desired value is a function of phase state and is dependent on frequency; it is n(22.5°) at the low end of the specified band; that is,

$$\Delta\phi = \frac{F}{F_L} n\ (22.5°)$$

where

F = is the operating frequency

F_L = low end of specified band

n = 0—15.

(U) The gain deviation listed, 1.55 dB, is that deviation over all frequencies in the specified band and for all 16 phase states. If considered with respect to the 1-dB bandwidth specification it can be interpreted that the module does not quite meet this specification at ± 5% about the center frequency. The maximum and minimum gain columns of Fig. 14 indicate that over the band, comparing all phase states, the 1-dB specification is exceeded. Note that the listings are per frequency, for all phase states. These data are shown in graphic form in Fig. 16. If a more lenient interpretation of the 1-dB bandwidth were assumed, one could select a single phase state. Figure 17 shows a plot of

RCA-1 gain vs frequency at the arbitrarily chosen phase state of 22.5 degrees. Even here, it is quite clear that the 1-dB limit of gain spread over the band is exceeded.

(S) The NRL interpretation of this basic specification has been that the 1-dB bandwidth shall be maintained over all voltage, phase, and temperature operating conditions. Admittedly, this may be a somewhat stringent interpretation if the use of modules in a phased array is considered. Over a physical spread of some 50 ft a reasonable temperature gradient of several degrees could be assumed, but a spread of -30°C to +70°C hardly seems likely. A supply voltage differential of ±2% from one end of the array to the other is probably possible but not too likely, particularly if a dedicated power source is used. However, over the array, any module could be in any phase state as long as the array beam was at some angle other than at broadside.

(U) The last column in Fig. 14 lists gain spread deviations over 20-MHz instantaneous bandwidths for all phases. The single asterisk indicates an out-of-specification (> 0.5 dB) condition within the specified band. Two asterisks indicate an out-of-specification condition outside the band. It becomes evident from all the module measurements that either the specification is too tight for the present state of the art or it is being too stringently interpreted. Deviations are determined by taking gain differences, minimum to maximum over 20-MHz bands, every 5 MHz. Perhaps the difference should be taken about an average rather than between maxima and minima.

(U) Figure 18 is a printout of measured module parameters for the zero phase state condition at room temperature, with all DC supply voltages low. The VSWR listing represents values measured at the module antenna port at frequencies shown. The VSWR specification is easily met both within and outside of the specified band. The gain within and outside the band meets the minimum specification. Of interest are the next three columns showing all zeroes. This is indicative of the data processing program in that the zero phase state data points are compared to themselves rather than to a theoretical set of data points associated with a best-fit line. Figure 19 shows the printout for the 22.5-degree phase state. Note that the differential phase is that computed with respect to the zero phase state, which is the reference for all the phase measurements. The 22.5-degree phase shift should have been obtained at the low end of the specified band.

```
MODULE ID:RCA-1 STANDARD RUNS      PROC. DATE:3/21/74
TAPE ID:  PRIME DATA               DATA DATE: 8/06/73
FILE ID:  RCA1 080673 0DEG         TEMP:      ROOM
FILE NO:  17   REF. FILE:  17      VOLT:      V-LOW
NEW PROGRAM

PHASE EQUIVALENT TO 148.09 CM AIRLINE WITH  11.89 DEGREE OFFSET
RMS ERROR IS     .87 DEGREES          PEAK ERROR IS  -1.67 DEGREES

BEST FIT QUADRATIC POLYNOMIAL COEFFICIENTS ARE:

          A(0):   .15265E+04
          A(1):  -.74392E+00
          A(2):  -.41316E-03
```

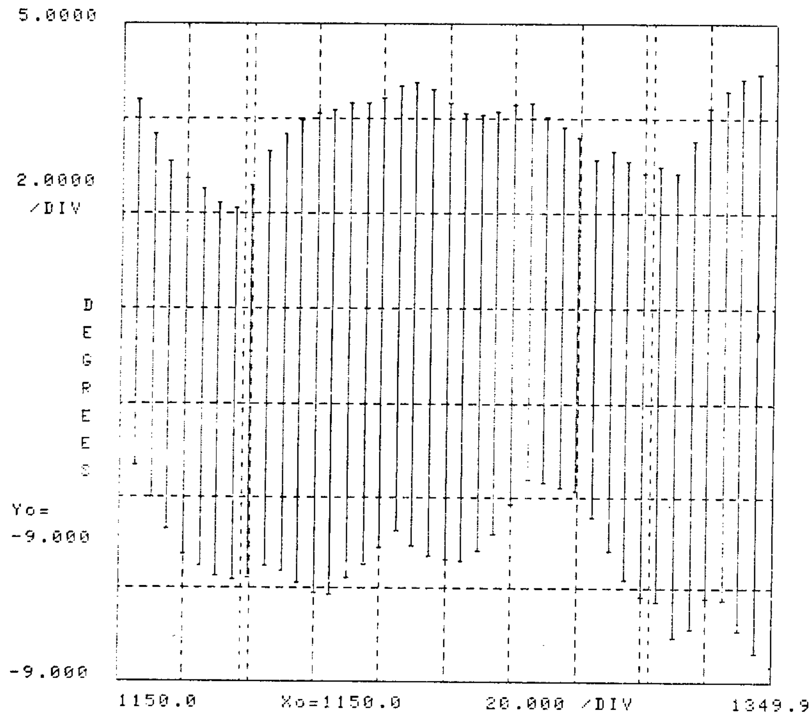
(S) Fig. 12 — Insertion phase data for specified band, RCA-1

FREQUENCY MHZ	LINEAR DEG	QUADRATIC DEG
1150.0	-2.24	1.38
1155.0	-2.80	.42
1160.0	-3.02	-.18
1165.0	-3.18	-.71
1170.0	-3.35	-1.22
1175.0	-2.44	-.63
1180.0	-2.14	-.63
1185.0	-1.49	-.26
1190.0	-1.25	-.28
1195.0	-.90	-.17
1200.0	-.33	.18
1205.0	-.28	.04
1210.0	-.46	-.32
1215.0	-.22	-.24
1220.0	-.22	-.38
1225.0	-.30	-.57
1230.0	-.11	-.47
1235.0	.66	.22
1240.0	.57	.07
1245.0	.82	.29
1250.0	.83	.30
1255.0	.95	.42
1260.0	1.10	.60
1265.0	1.19	.74
1270.0	1.39	1.01
1275.0	.92	.63
1280.0	.62	.44
1285.0	.21	.17
1290.0	-.11	-.00
1295.0	-.64	-.35
1300.0	-1.17	-.69
1305.0	-1.67	-.98
1310.0	-1.59	-.66
1315.0	-1.49	-.30
1320.0	-2.38	-.91
1325.0	-2.13	-.36
1330.0	-1.77	.32
1335.0	-1.74	.69
1340.0	-1.54	.84
1345.0	-2.43	.73
1349.9	-3.21	.34

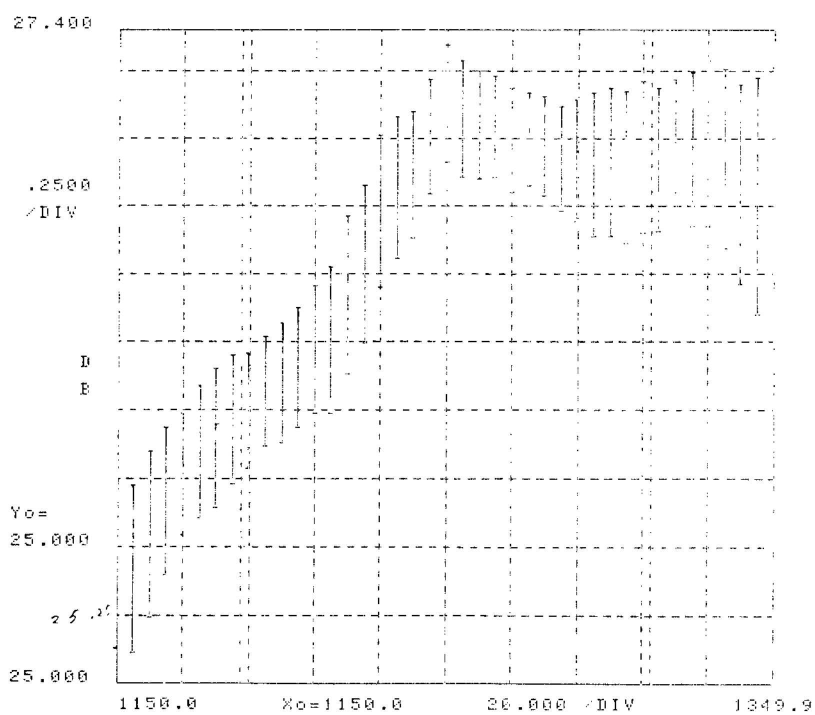
(S) Fig. 13 — Insertion phase errors, RCA-1

FREQ	MAX GAIN	MIN GAIN	DEL GAIN	I. BAND DEV
1150.0	25.67	25.05	.62	.94**
1155.0	25.73	25.11	.61	.98**
1160.0	25.85	25.25	.61	.90**
1165.0	25.94	25.40	.54	.80**
1170.0	25.99	25.54	.45	.57**
1175.0	26.09	25.61	.48	.66**
1180.0	26.15	25.64	.51	.48**
1185.0	26.20	25.73	.47	.64**
1190.0	26.21	25.79	.42	.66*
1195.0	26.27	25.87	.40	.66*
1200.0	26.32	25.88	.44	.83*
1205.0	26.38	25.94	.44	.09*
1210.0	26.46	25.99	.46	1.03*
1215.0	26.53	25.99	.54	1.10*
1220.0	26.71	26.13	.58	.97*
1225.0	26.83	26.25	.58	.98*
1230.0	27.02	26.45	.57	.90*
1235.0	27.08	26.55	.53	.79*
1240.0	27.10	26.63	.47	.71*
1245.0	27.22	26.79	.43	.55*
1250.0	27.34	26.91	.43	.54*
1255.0	27.29	26.86	.43	.48
1260.0	27.25	26.85	.40	.46
1265.0	27.23	26.86	.37	.50*
1270.0	27.19	26.80	.38	.49
1275.0	27.17	26.82	.35	.53*
1280.0	27.16	26.79	.36	.55*
1285.0	27.12	26.73	.39	.57*
1290.0	27.14	26.69	.45	.60*
1295.0	27.17	26.64	.53	.69*
1300.0	27.19	26.64	.55	.61*
1305.0	27.18	26.61	.56	.63*
1310.0	27.21	26.65	.56	.64*
1315.0	27.19	26.66	.53	.49**
1320.0	27.22	26.69	.54	.83**
1325.0	27.25	26.68	.57	.94**
1330.0	27.29	26.68	.61	1.04**
1335.0	27.26	26.60	.66	
1340.0	27.20	26.46	.74	
1345.0	27.23	26.35	.88	
1349.9	27.26	26.25	1.01	

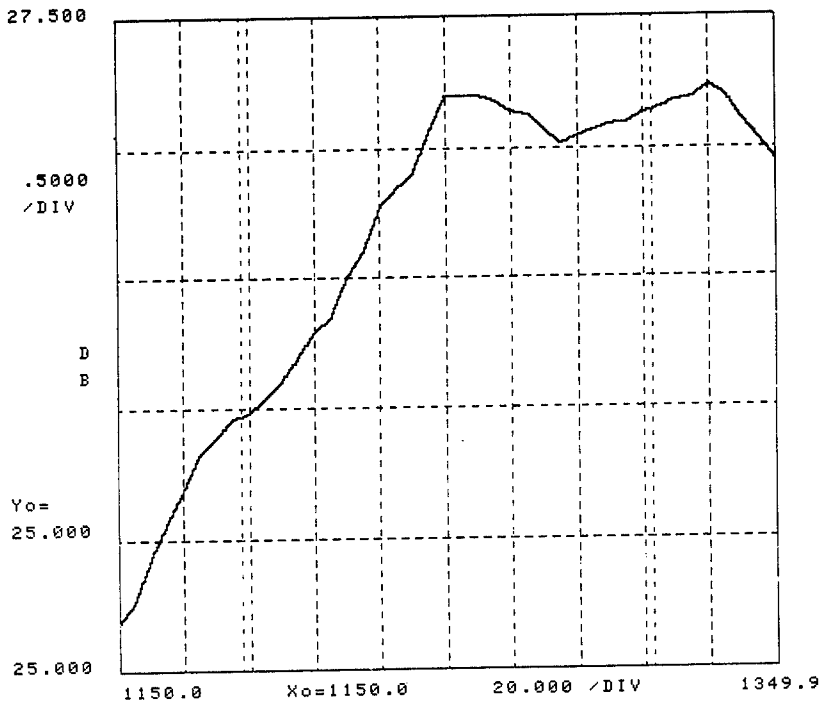
(S) Fig. 14 — Data summary, RCA-1



(S) Fig. 15 — Differential phase error spread vs frequency, RCA-1 V-Low 2% below nominal supply voltage



(S) Fig. 16 — Gain spread vs frequency, RCA-1, V-Low



(S) Fig. 17 — Gain vs frequency, RCA-1

FREQ	VSWR	GAIN	D. PHASE	ERROR	D. SLOPE
1150.0	1.20	25.06	.00	.00	.000
1155.0	1.17	25.11	.00	.00	.000
1160.0	1.14	25.25	.00	.00	.000
1165.0	1.11	25.40	.00	.00	.000
1170.0	1.09	25.55	.00	.00	.000
1175.0	1.07	25.71	.00	.00	.000
1180.0	1.06	25.80	.00	.00	.000
1185.0	1.05	25.91	.00	.00	.000
1190.0	1.06	25.96	.00	.00	.000
1195.0	1.06	26.06	.00	.00	.000
1200.0	1.07	26.12	.00	.00	.000
1205.0	1.07	26.19	.00	.00	.000
1210.0	1.07	26.29	.00	.00	.000
1215.0	1.07	26.38	.00	.00	.000
1220.0	1.07	26.55	.00	.00	.000
1225.0	1.06	26.65	.00	.00	.000
1230.0	1.06	26.83	.00	.00	.000
1235.0	1.05	26.90	.00	.00	.000
1240.0	1.03	26.95	.00	.00	.000
1245.0	1.02	27.07	.00	.00	.000
1250.0	1.00	27.18	.00	.00	.000
1255.0	1.01	27.19	.00	.00	.000
1260.0	1.02	27.21	.00	.00	.000
1265.0	1.03	27.23	.00	.00	.000
1270.0	1.05	27.19	.00	.00	.000
1275.0	1.06	27.17	.00	.00	.000
1280.0	1.07	27.16	.00	.00	.000
1285.0	1.08	27.12	.00	.00	.000
1290.0	1.09	27.10	.00	.00	.000
1295.0	1.10	27.06	.00	.00	.000
1300.0	1.10	27.07	.00	.00	.000
1305.0	1.10	27.10	.00	.00	.000
1310.0	1.10	27.14	.00	.00	.000
1315.0	1.10	27.13	.00	.00	.000
1320.0	1.11	27.21	.00	.00	.000
1325.0	1.12	27.25	.00	.00	.000
1330.0	1.14	27.29	.00	.00	.000
1335.0	1.15	27.26	.00	.00	.000
1340.0	1.14	27.13	.00	.00	.000
1345.0	1.13	27.04	.00	.00	.000
1349.9	1.11	26.98	.00	.00	.000

(S) Fig. 18 — Comparison file data, RCA-1, 0 degrees

FREQ	VSWR	GAIN	D. PHASE	ERROR	D. SLOPE
1150.0	1.21	25.18	22.05	.26	-.039
1155.0	1.19	25.27	22.23	.34	-.052**
1160.0	1.16	25.43	22.14	.16	-.055**
1165.0	1.13	25.56	21.94	-.13	-.053**
1170.0	1.10	25.69	21.70	-.47	-.048
1175.0	1.08	25.82	21.63	-.64	-.035
1180.0	1.06	25.88	21.40	-.95	-.018
1185.0	1.05	25.96	21.24	-1.21	-.009
1190.0	1.05	25.98	21.18	-1.37	-.019
1195.0	1.05	26.03	21.33	-1.31	-.039
1200.0	1.05	26.10	21.40	-1.34	-.043
1205.0	1.06	26.19	21.37	-1.46	-.037
1210.0	1.06	26.29	21.16	-1.76	-.022
1215.0	1.06	26.34	20.96	-2.07	-.009
1220.0	1.05	26.50	21.00	-2.11	-.006
1225.0	1.05	26.60	21.00	-2.21	-.002
1230.0	1.04	26.77	21.07	-2.23	-.007
1235.0	1.03	26.85	21.18	-2.22	-.021
1240.0	1.02	26.90	21.25	-2.25	-.033
1245.0	1.01	27.06	21.34	-2.25	-.027
1250.0	1.01	27.20	21.28	-2.40	.009
1255.0	1.02	27.20	21.11	-2.67	.031
1260.0	1.04	27.20	21.02	-2.85	.018
1265.0	1.05	27.19	21.28	-2.69	.001
1270.0	1.06	27.14	21.91	-2.16	.002
1275.0	1.07	27.13	21.90	-2.25	.020
1280.0	1.08	27.07	21.64	-2.62	.025
1285.0	1.09	27.02	21.92	-2.42	-.007
1290.0	1.09	27.05	22.41	-2.03	-.031
1295.0	1.10	27.07	22.49	-2.05	-.029
1300.0	1.10	27.09	22.44	-2.19	-.059*
1305.0	1.10	27.10	22.20	-2.53	-.073*
1310.0	1.11	27.14	22.25	-2.57	-.042
1315.0	1.11	27.15	22.34	-2.58	-.000
1320.0	1.13	27.19	21.37	-3.64	.042
1325.0	1.15	27.19	21.26	-3.84	.015
1330.0	1.17	27.24	22.21	-2.99	-.040
1335.0	1.18	27.20	22.39	-2.91	.000
1340.0	1.17	27.11	22.33	-3.06	.000
1345.0	1.16	27.03	22.06	-3.42	.000
1349.9	1.14	26.95	21.84	-3.74	.000

(S) Fig. 19 — Comparison file data, RCA-1, 22.5 degrees

(U) The differential slope (last column listing in Fig. 19) is the phase rate of change per 10 MHz calculated over 20-MHz instantaneous band spaced 5 MHz apart within the overall band. The single and twin asterisk arrangement of specification conformance within and outside the specified band is again used. Although at this particular phase state the RCA-1 module showed few out-of-specification points, at the other phase states many such points were found.

(U) Figure 20 is a plot of VSWR vs frequency for the RCA-1 receiver; VSWR was measured at the antenna port. Although the specification (1.4) is adequately met, it is clear that VSWR starts to deteriorate at the upper band edge and beyond. Here, the designer has lost control of this characteristic, as evidenced by the increase in maximum VSWR as well as the increased spread from minimum to maximum.

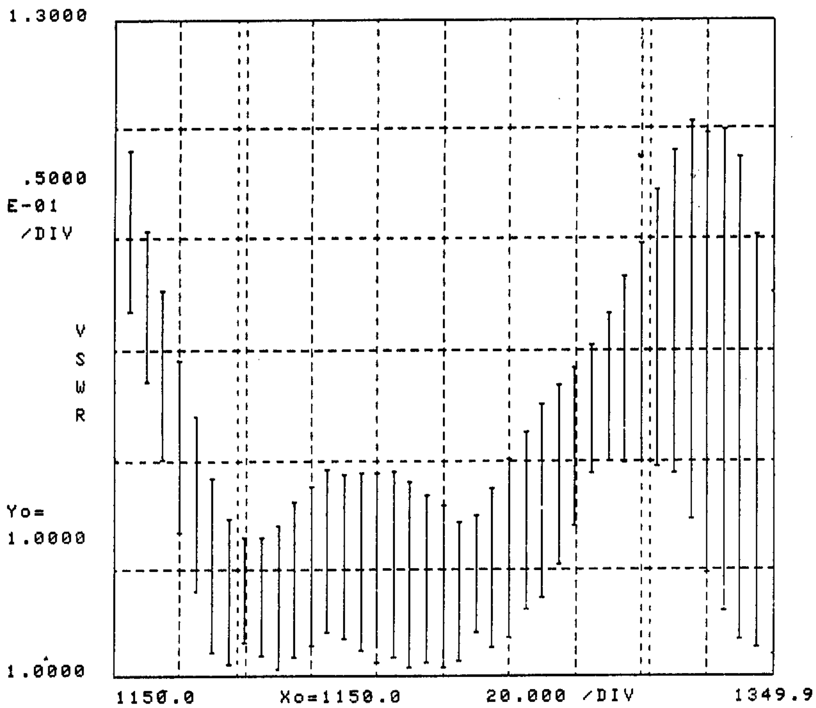
(U) Figure 21 is a histogram of gain over all phases and frequencies when the supply voltage is low vs the number of times particular gain values were measured. For instance, there were 71 measurements of 27.1-dB gain, 21 measurements of 26.6-dB gain, etc. The histogram shows the type of distribution of measurements, such as bell-shaped curve. It also serves as a quality factor indicator by giving a quantitative indication of the spread of measurements. Here again it can be seen that the 1-dB bandwidth specification is exceeded even though frequency is not a coordinate. If the maximum gain were to be 27.2 dB and the minimum 26.2 dB, then 53 points below 26.2 dB would have to be shifted to the right (higher gain) and two above 27.2 dB shifted to the left (lower gain) by some means, in order to fulfill specified requirements. This is equivalent to moving 55 out of 400 points, or 13.75% of the points.

(U) Figure 22 is a histogram of differential phase error vs the number of data points per value. It serves a similar purpose with respect to phase as Fig. 21 did to gain. Note that for both histograms only the specified band was considered. For Fig. 21, 16 phase states yielded 400 points, whereas for Fig. 22, 15 phase states were compared to the zero phase state for a maximum of 375 points.

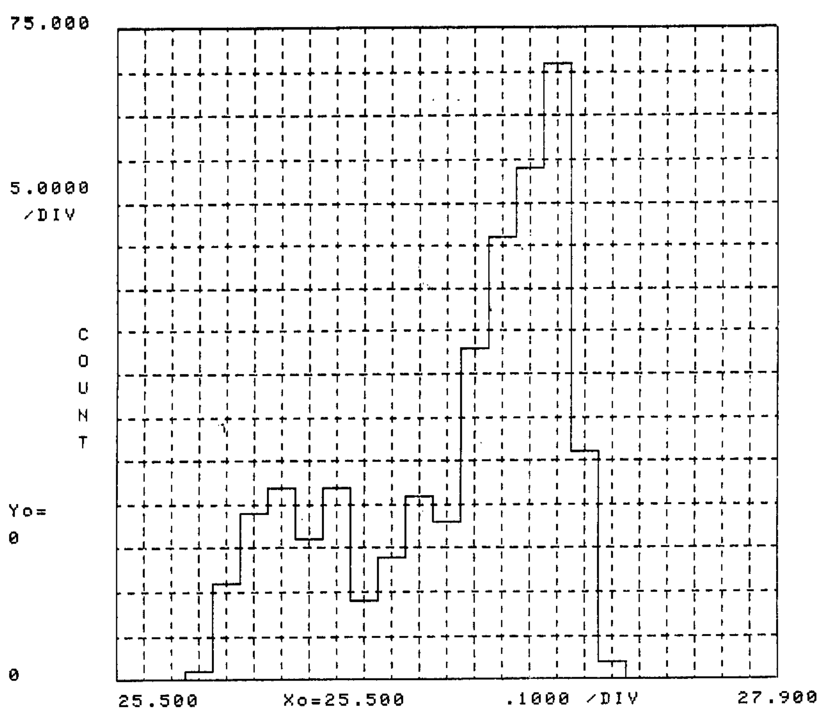
(U) Figures 23 and 24 show the effects of raising the receiver power supply voltages to nominal and 2% above nominal. The general shapes and gain spreads are the same as those of the plot for 2% below nominal supply voltage (Fig. 16). The gains, however, varied directly as the power supply voltages, which was expected.

(U) Figures 25 and 26 show the variation of differential phase error spread as the supply voltage is moved to V-Nom (nominal) and V-High (2% above nominal). As can be seen, compared to V-Low (2% below nominal), the magnitudes of the spreads remained substantially the same but varied along the ordinate almost randomly on a per-frequency basis. The maximum phase change was well within the 0.5-degree (cumulative) specification.

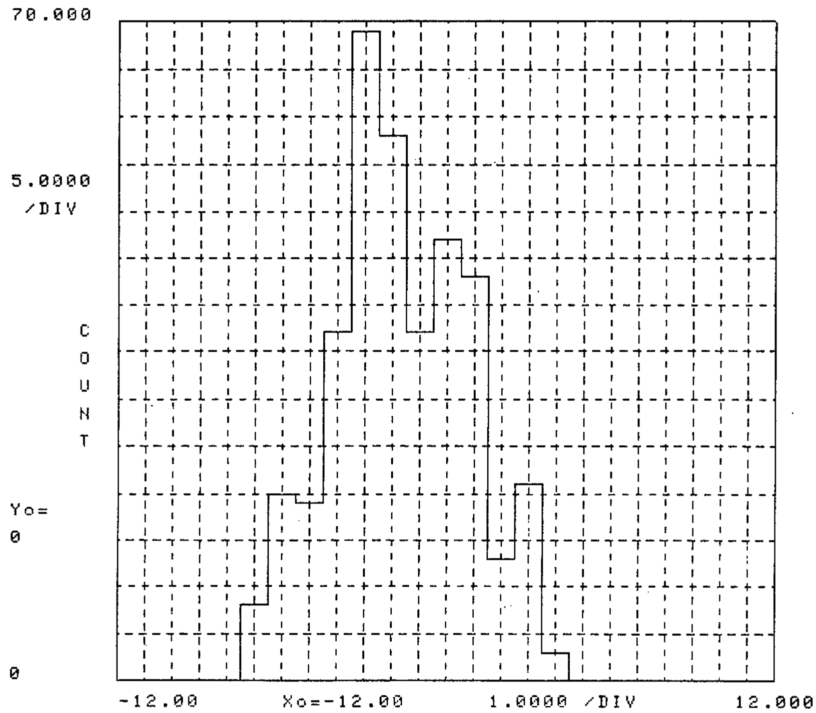
(U) Figures 27 and 28 show the VSWR spread vs frequency for nominal and high supply voltages, respectively. Compared to low voltage, the general shape is maintained but the spreads of VSWR increase slowly but progressively as the supply voltage increases.



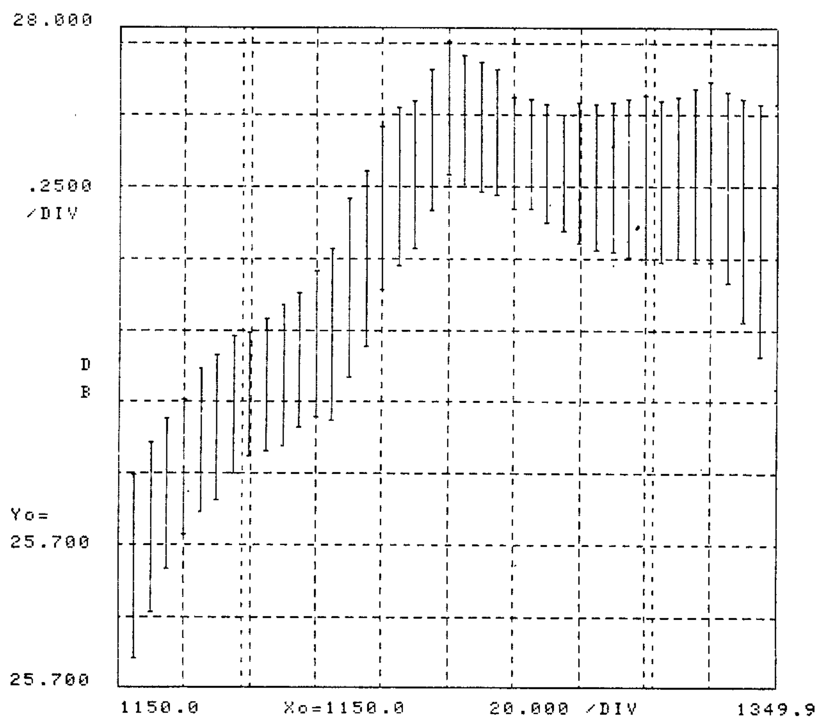
(S) Fig. 20 — VSWR spread vs frequency, RCA-1, V-Low



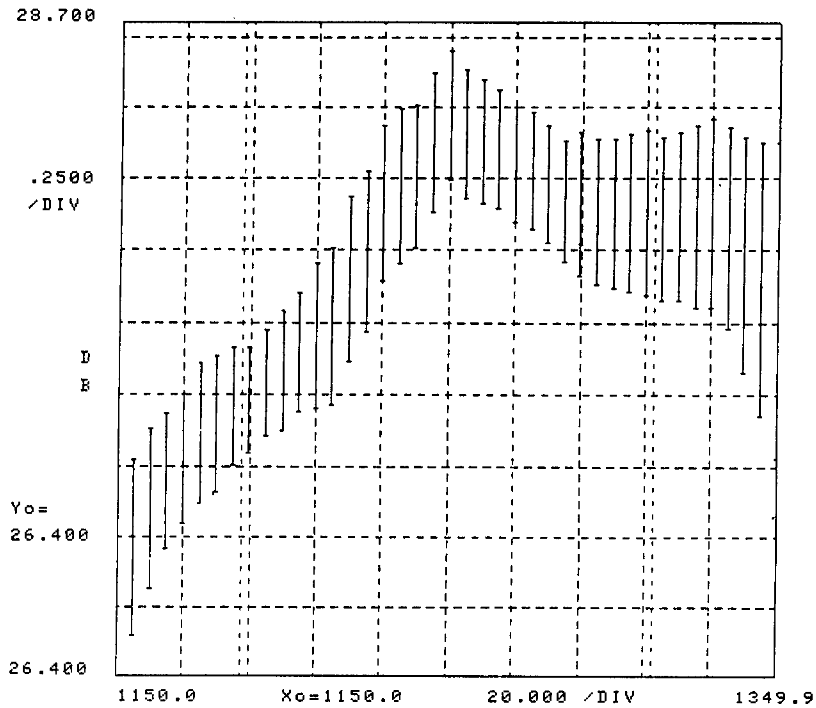
(S) Fig. 21 — Gain histogram, RCA-1, V-Low



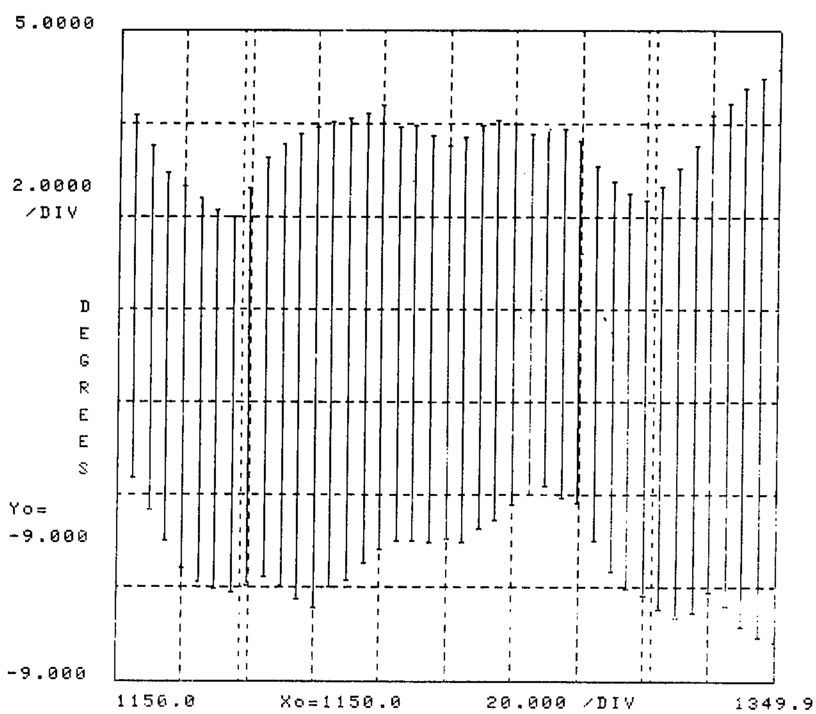
(S) Fig. 22 — Differential phase error histogram, RCA-1, V-Low



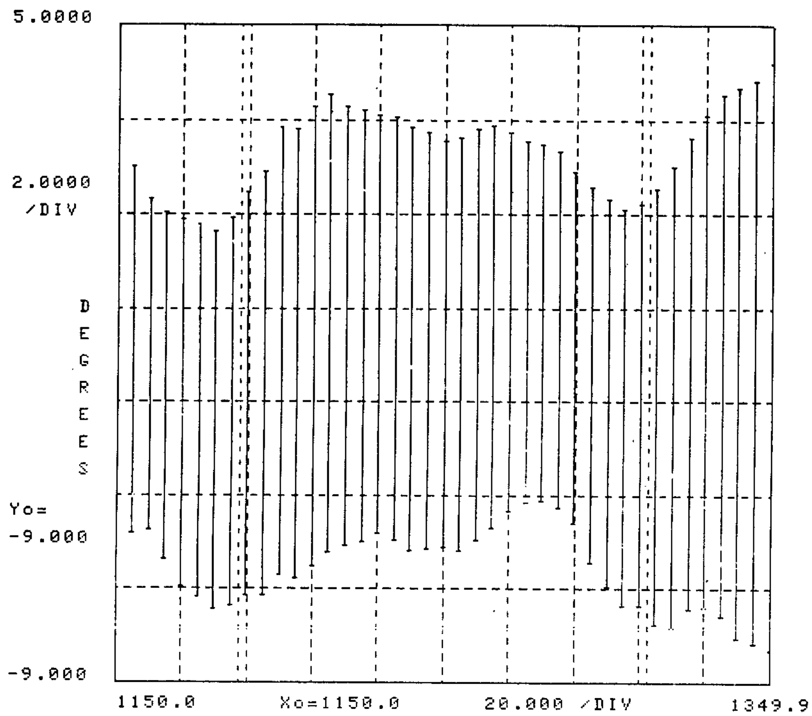
(S) Fig. 23 — Gain spread vs frequency, RCA-1, V-Nom



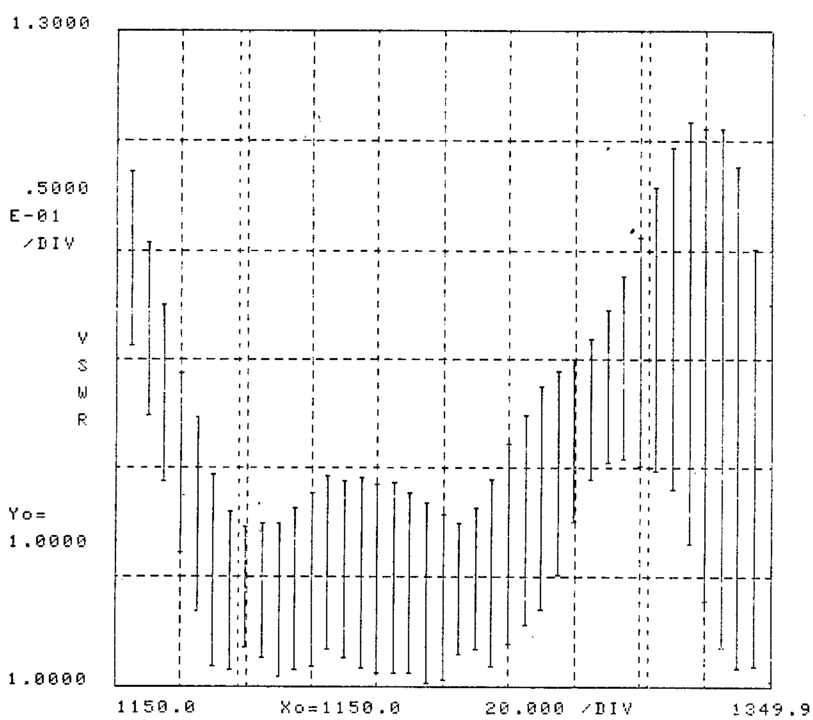
(S) Fig. 24 — Gain spread vs frequency, RCA-1, V-High



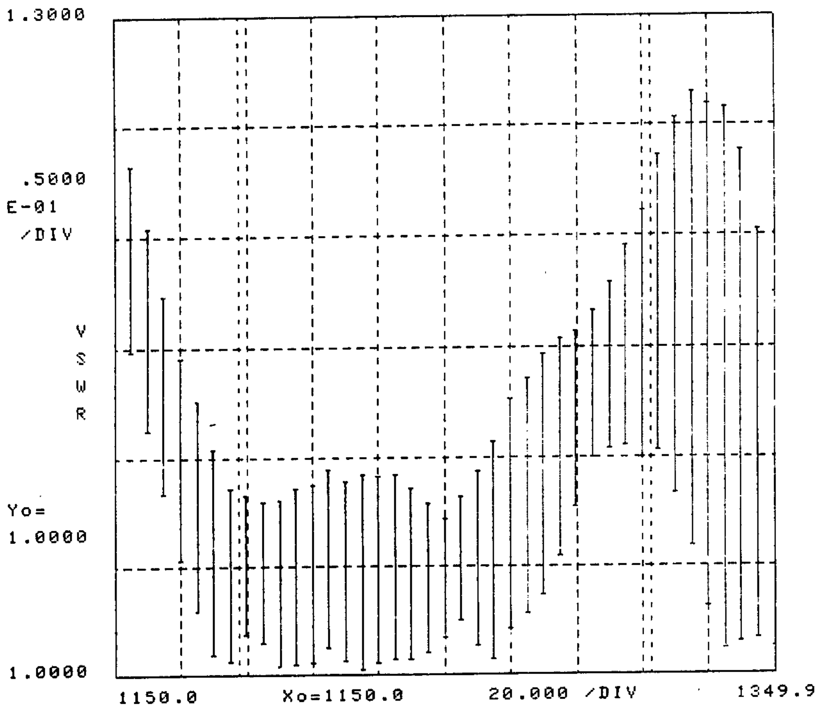
(S) Fig. 25 — Differential phase error spread vs frequency, RCA-1, V-Nom



(S) Fig. 26 — Differential phase error spread vs frequency, RCA-1, V-High



(S) Fig. 27 — VSWR spread vs frequency, RCA-1, V-Nom

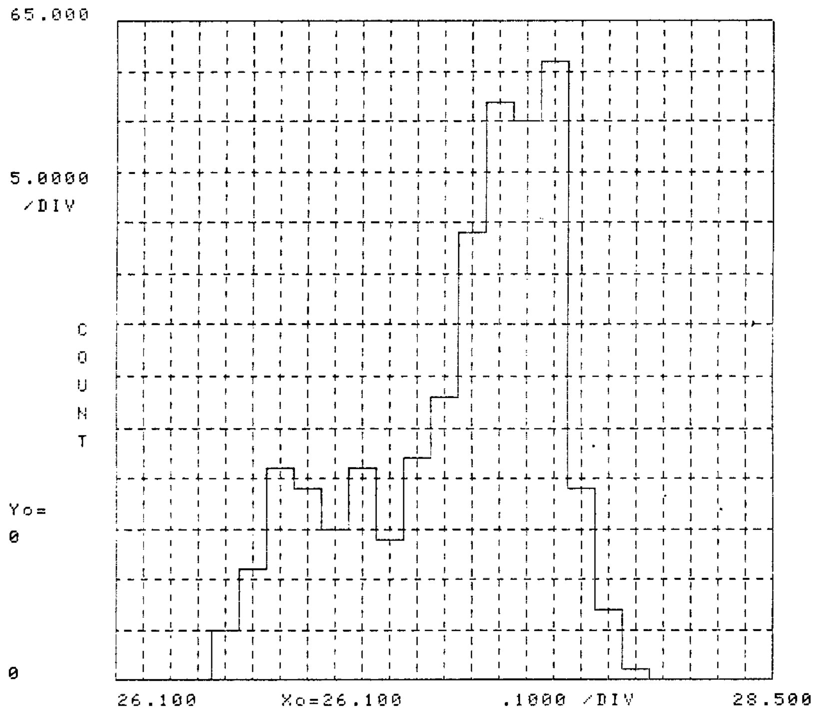


(S) Fig. 28 — VSWR spread vs frequency, RCA-1, V-High

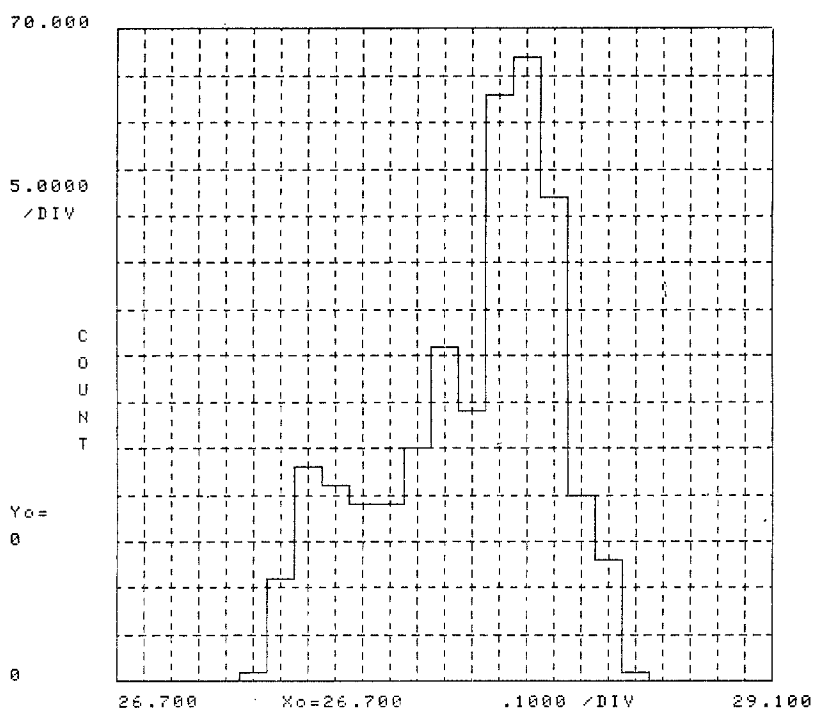
(U) Figures 29 and 30 are the gain histograms for nominal and high voltages, respectively. Compared with that for low voltage, while exhibiting similar physical structures, the areas under the curves for the higher supply voltages increased somewhat at the lower gains. The plots, of course, also indicate the overall increase of receiver gain with increased voltages.

(U) Figures 31 and 32 are the differential phase error histograms for nominal and high voltages, respectively. Compared to low voltage, with increasing supply voltage the numbers of points increase considerably at 0 degrees as well as -2 degrees at the expense of the points at ± 1 degrees, -4, and -5 degrees. In other words the center of the curve moved somewhat positively in phase with increasing supply voltage. This was probably because the diodes in the phase shifter conducted more heavily as the voltage across them was increased.

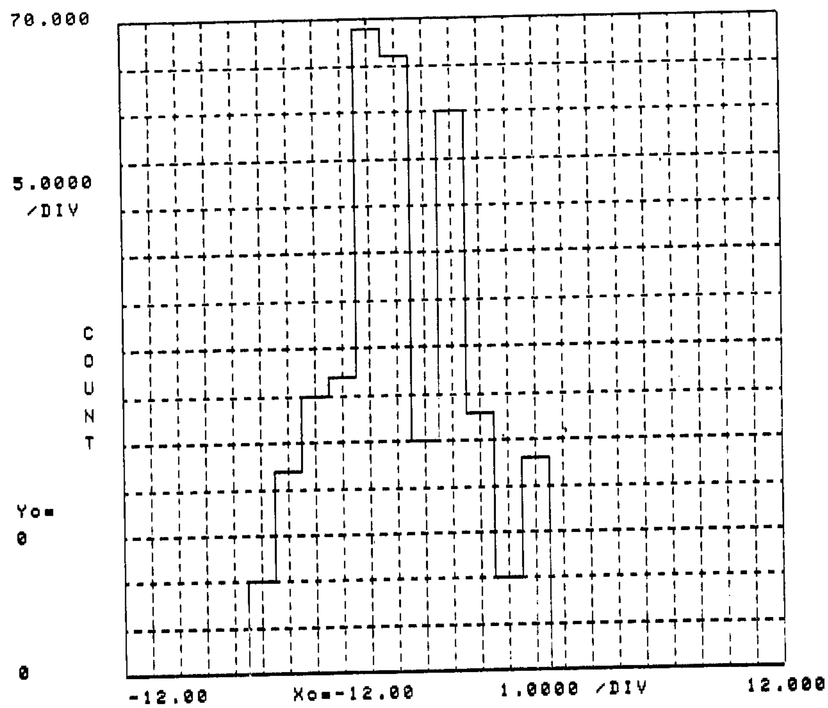
(U) Figures 33, 34, and 35 show gain spreads vs frequency for the RCA-2 receiver with low, nominal, and high supply voltages. The curvatures of the spreads follow those of RCA-1 almost exactly, although the gains of RCA-2 are all higher.



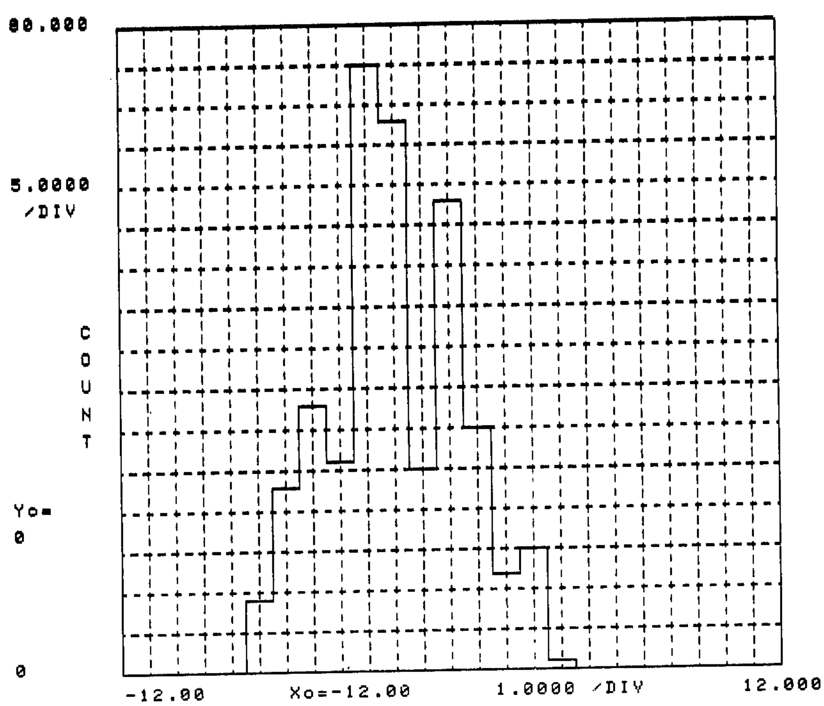
(U) Fig. 29 — Gain histogram, RCA-1, V-Nom



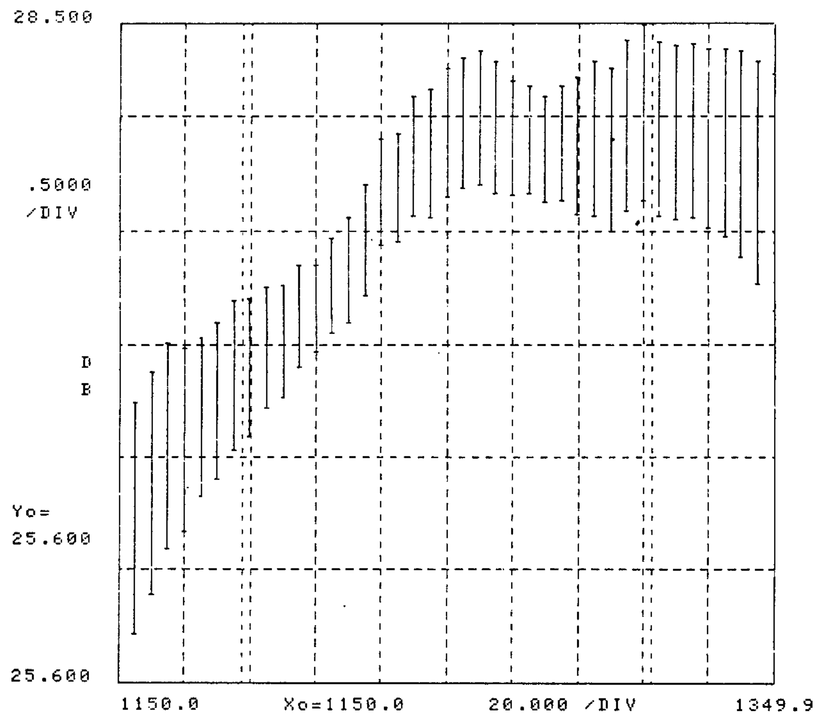
(U) Fig. 30 — Gain histogram, RCA-1, V-High



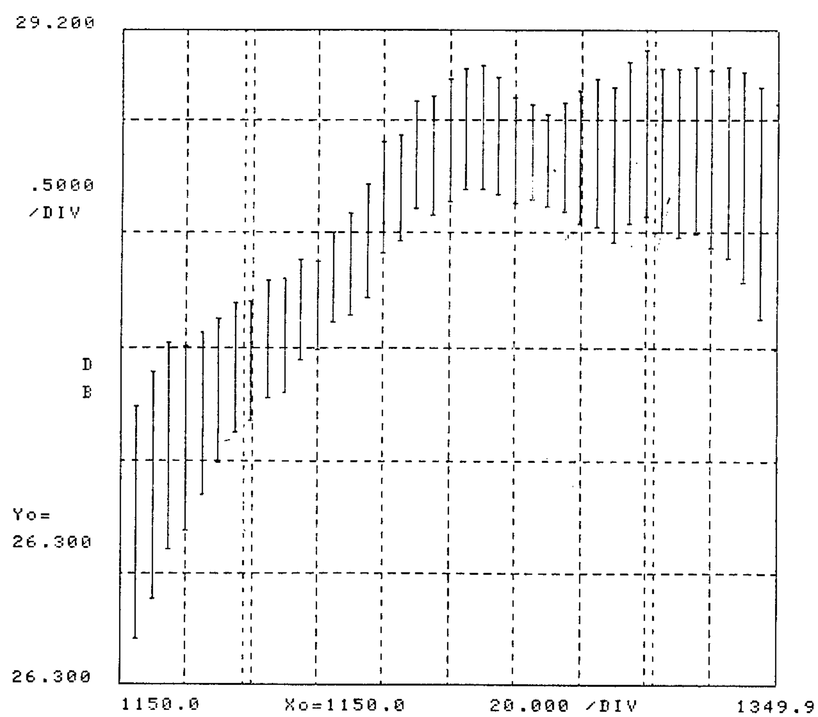
(U) Fig. 31 — Differential phase error histogram, RCA-1, V-Nom



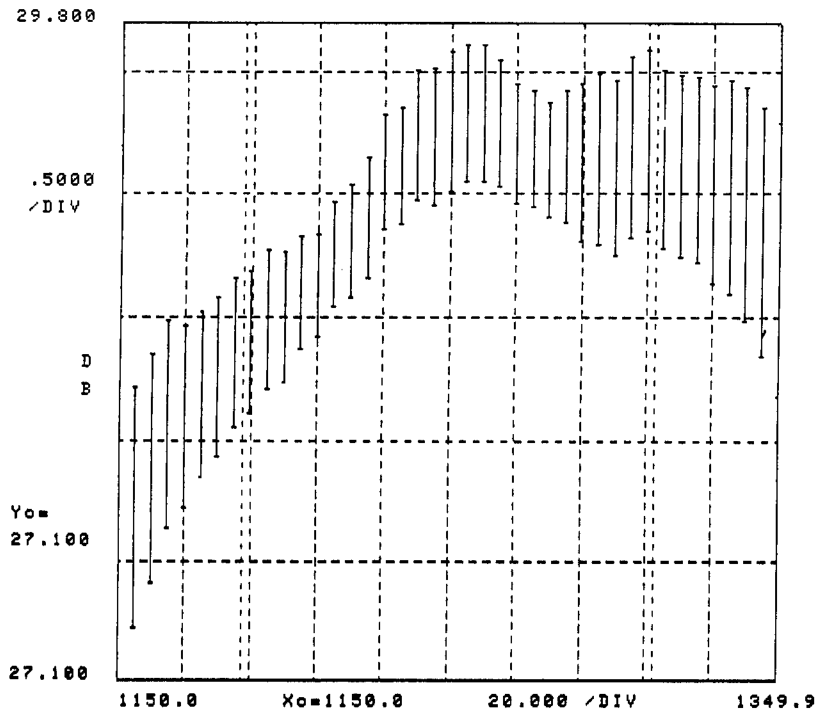
(U) Fig. 32 — Differential phase error histogram, RCA-1, V-High



(S) Fig. 33 — Gain spread vs frequency, RCA-2, V-Low



(S) Fig. 34 — Gain spread vs frequency, RCA-2, V-Nom

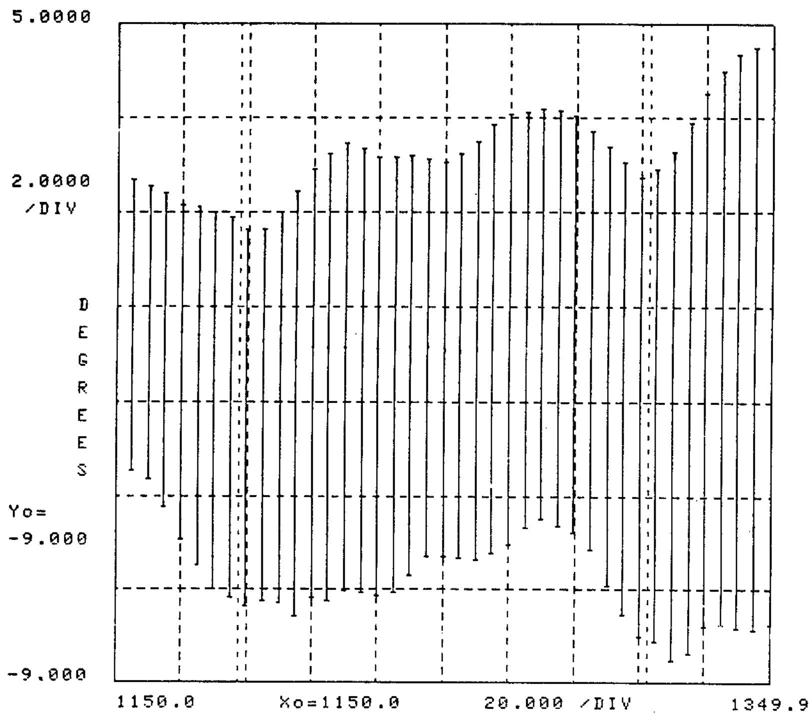


(S) Fig. 35 — Gain spread vs frequency, RCA-2, V-High

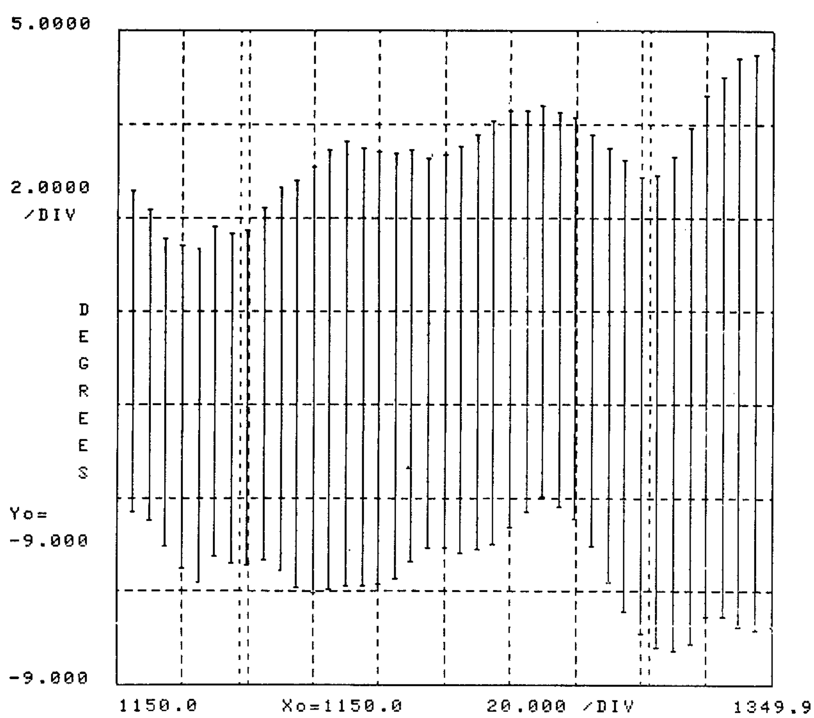
(U) The differential phase error vs frequency plots for RCA-2, Figs. 36, 37, and 38 (under similar power supply variations), also follow those of RCA-1. In the case of RCA-2 there is an extremely small phase change per frequency as the supply voltage is varied. Both differential phase and phase variation with supply voltage are well within specification.

(U) The spreads of VSWR vs frequency for RCA-2, Figs. 39, 40, and 41, stay within limits inside the specified band but progressively get out of hand as the frequency drops below 1165 MHz. The VSWR appears to be relatively unaffected by changes in supply voltage. If comparing VSWR plots of RCA-2 with those of RCA-1, note that although the spreads of RCA-2 appear to be more consistent, the scales of the ordinates are different and the excursions of its VSWR as shown are compressed relative to those shown for RCA-1.

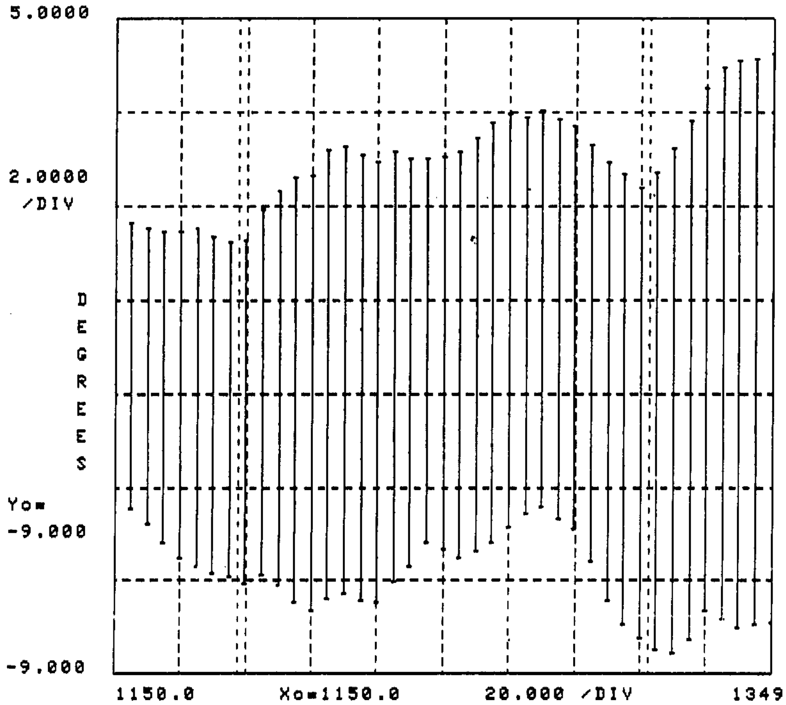
(U) Figures 42, 43, and 44 show the gain spreads vs frequency from V-low to V-high voltage for the Microwave Associates MA-1 receiver. Predictably, the receiver gain followed the supply voltage increases. The large spreads of gain per frequency probably are not functions of supply voltage variations as can be seen by comparing Figs. 43 and 44 (which have similar scales). The spreads are more likely due to losses attributable to the phase shifter as the module is moved through its range of phase states. As can be noted on all three plots, the spread at center frequency is approximately 1.5 dB, a considerable amount.



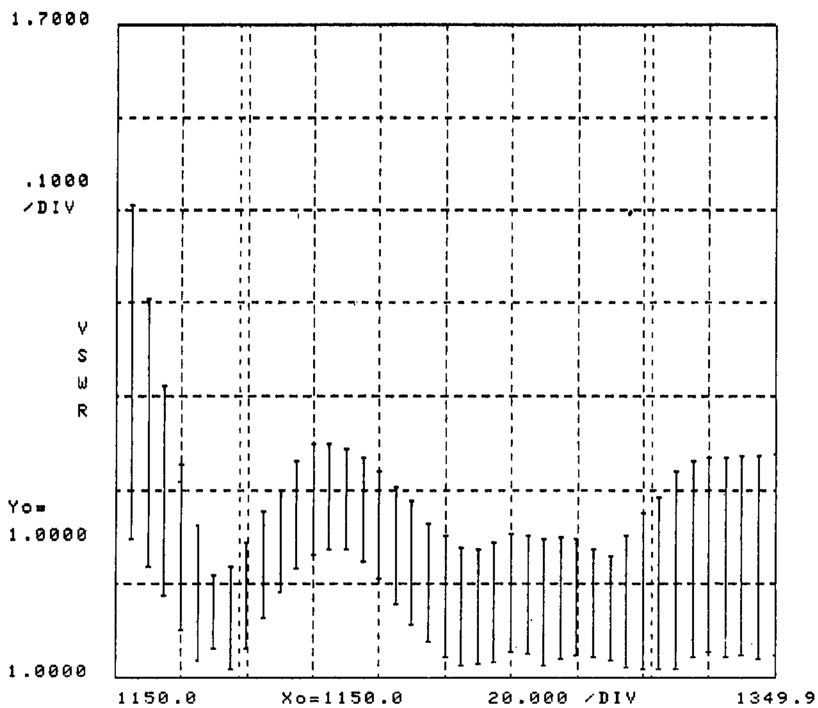
(S) Fig. 36 — Differential phase error spread vs frequency, RCA-2, V-Low



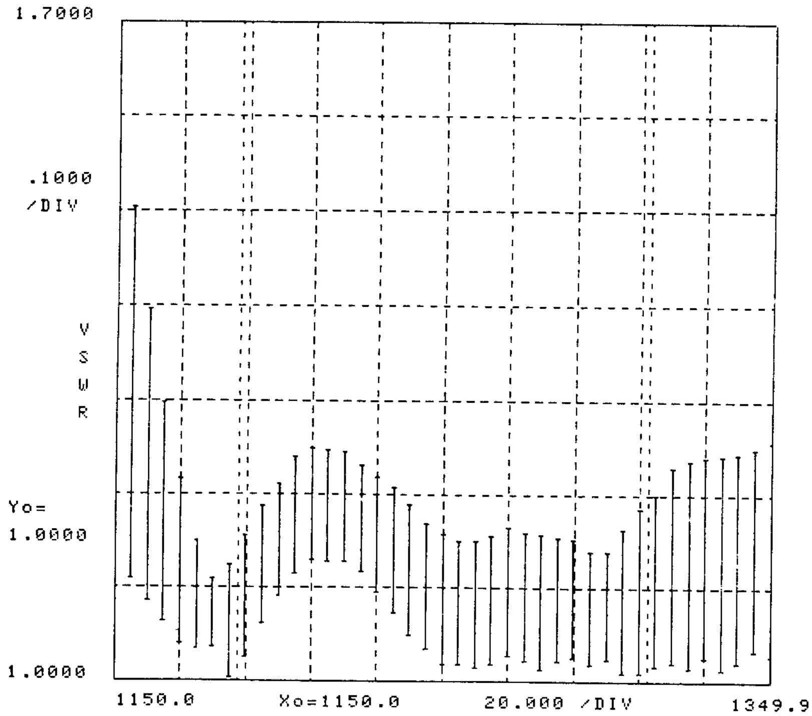
(S) Fig. 37 — Differential phase error spread vs frequency, RCA-2, V-Nom



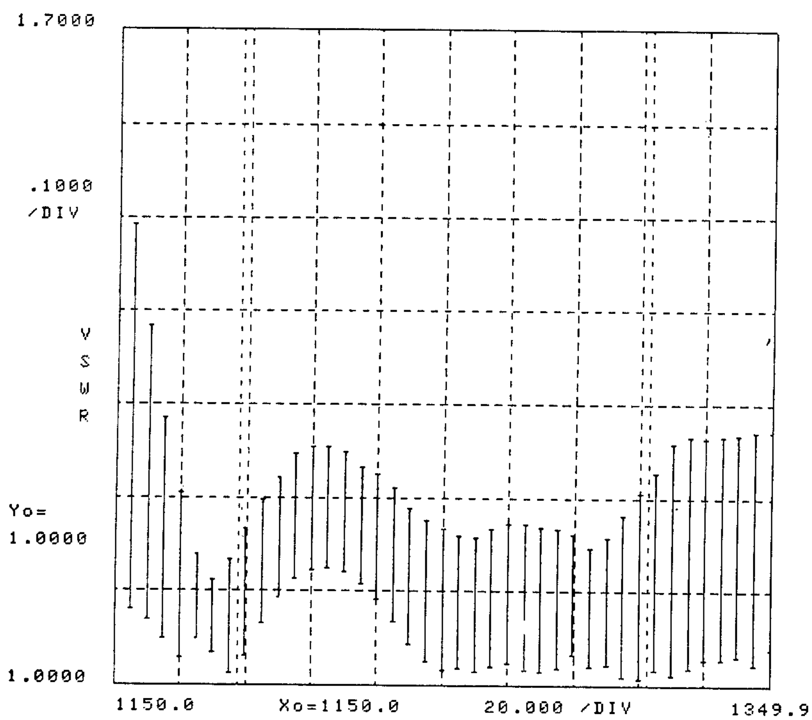
(S) Fig. 38 — Differential phase error spread vs frequency, RCA-2, V-High



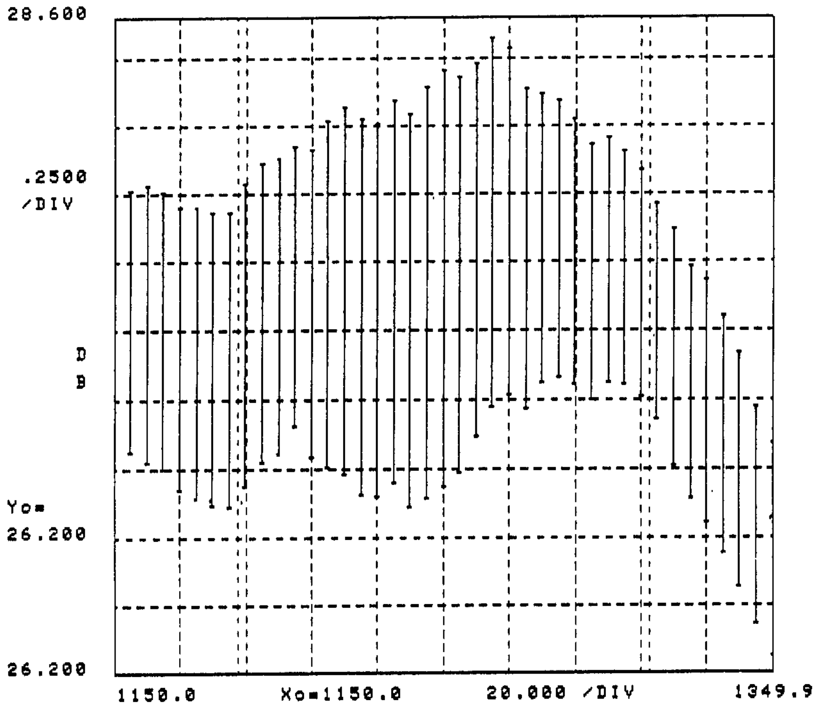
(S) Fig. 39 — VSWR spread vs frequency, RCA-2, V-Low



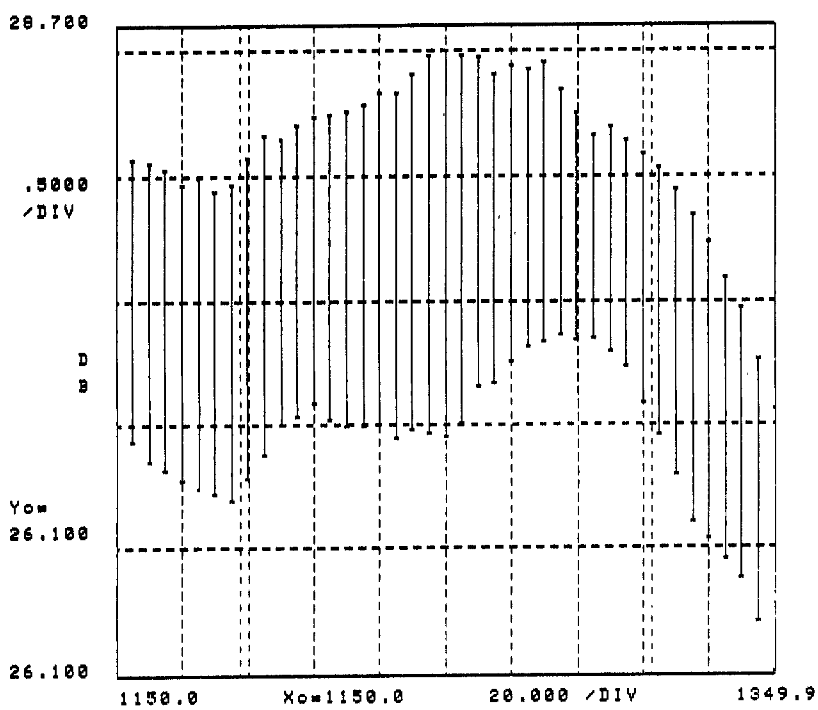
(S) Fig. 40 — VSWR spread vs frequency, RCA-2, V-Nom



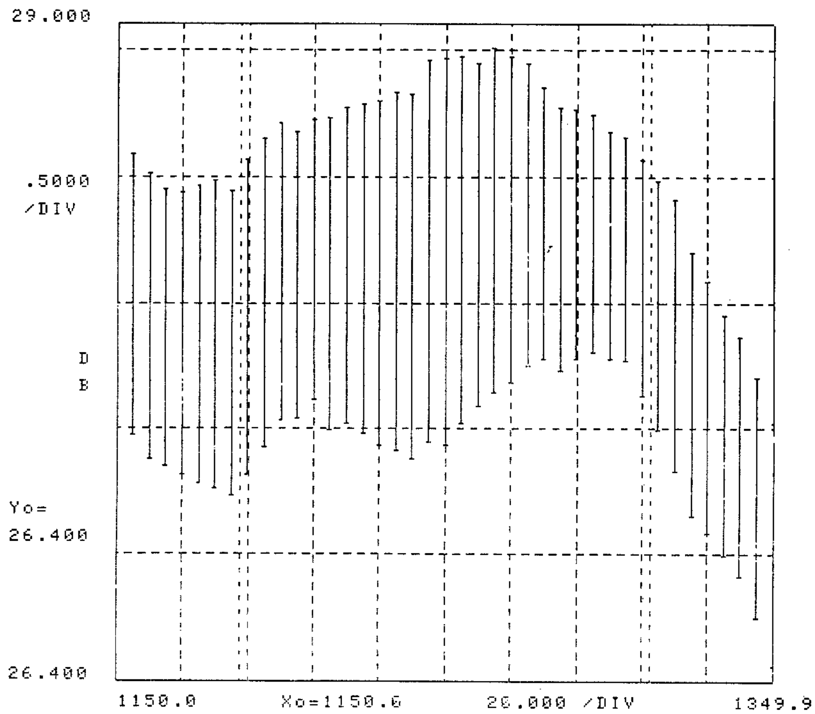
(S) Fig. 41 — VSWR spread vs frequency, RCA-2, V-High



(S) Fig. 42 — Gain spread vs frequency, MA-1, V-Low



(S) Fig. 43 — Gain spread vs frequency, MA-1, V-Nom

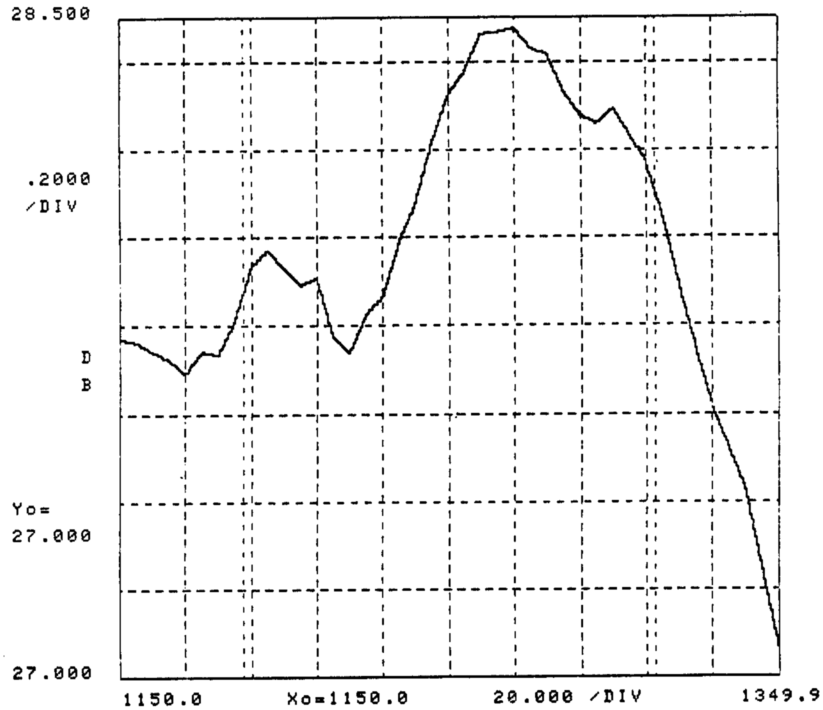


(S) Fig. 44 — Gain spread vs frequency, MA-1, V-Nom

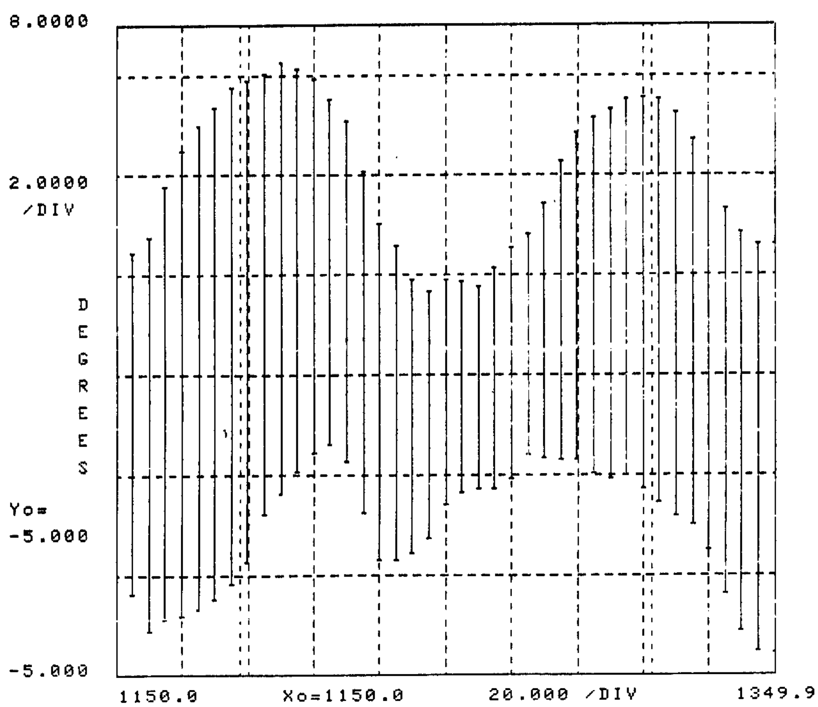
(U) Although the gain spread plots show that the 1-dB bandwidth specification was not met overall, for many individual phase states at a given supply voltage this was not the case, as typified by Fig. 45. Here, for the 22.5-degree phase state the maximum gain variation over the specified band can be seen to be approximately 0.7 dB.

(U) Differential phase error spreads vs frequency for receiver MA-1 are shown in Figs. 46, 47, and 48. Although the differential phase error specification is met, it is interesting to note that the greatest phase changes, as much as 2 degrees, occur as the supply voltage is either reduced or increased from the nominal rather than between the high and low supply voltages. This can also be seen in Fig. 49, which is made up of three superimposed plots of differential phase vs frequency for the 22.5-degree phase state for low, nominal, and high supply voltages. (This particular phase state was arbitrarily chosen.)

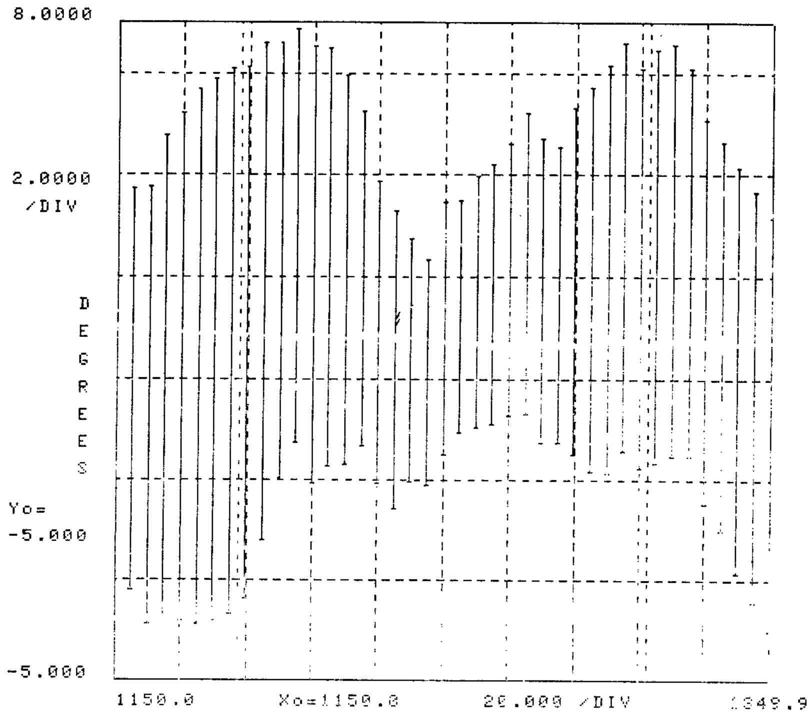
(U) Figures 50, 51, and 52 show VSWR spreads with frequency for receiver MA-1 at low, nominal, and high voltages. The VSWRs can be seen to be independent of power supply variations and phase states (note the small per-frequency spread). Although within specification, there is considerable variation of VSWR, with maxima slightly higher than the RCA receivers within the specified band.



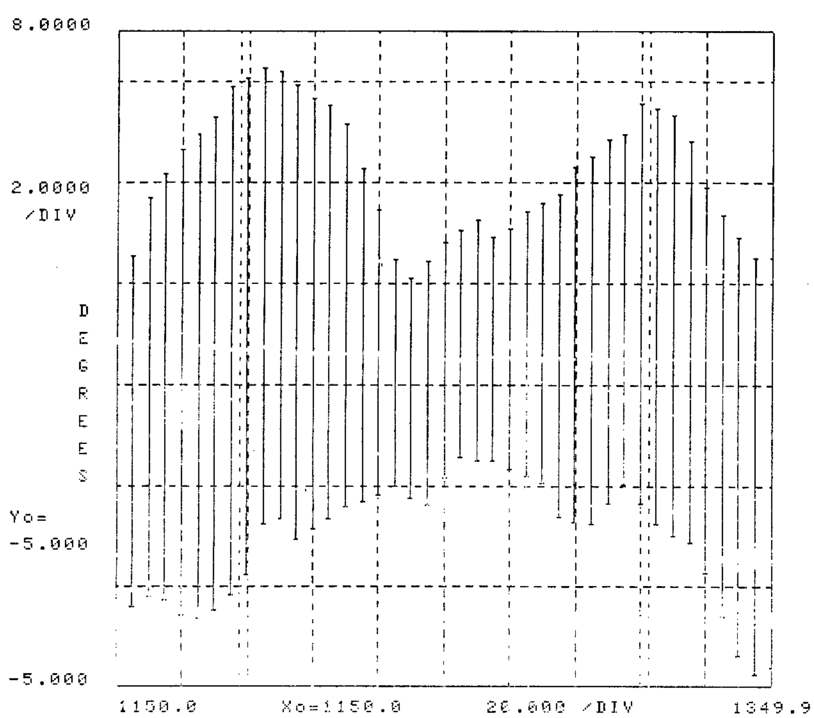
(S) Fig. 45 — Gain vs frequency, MA-1, V-Nom



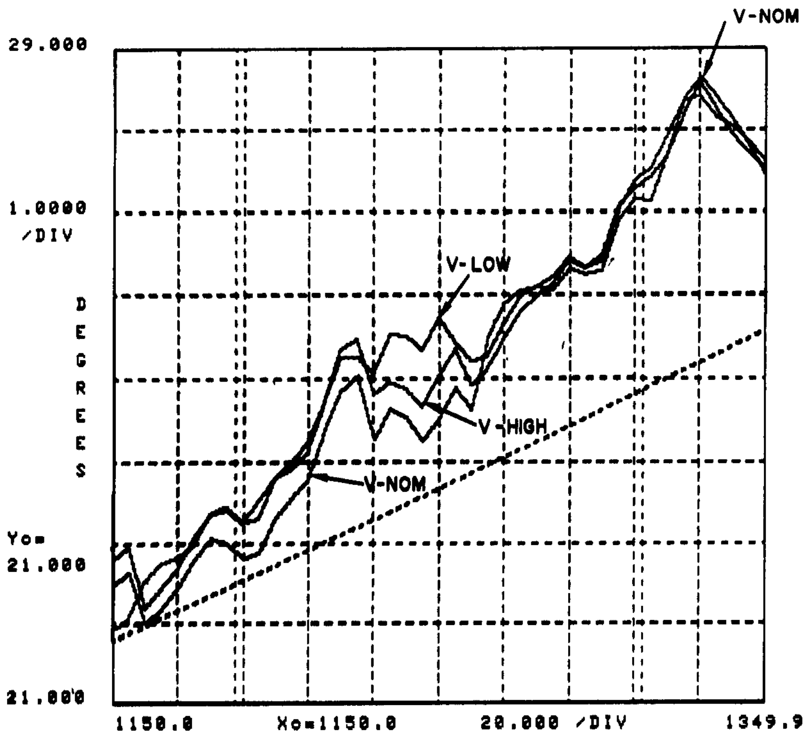
(S) Fig. 46 — Differential phase error spread vs frequency, MA-1, V-Low



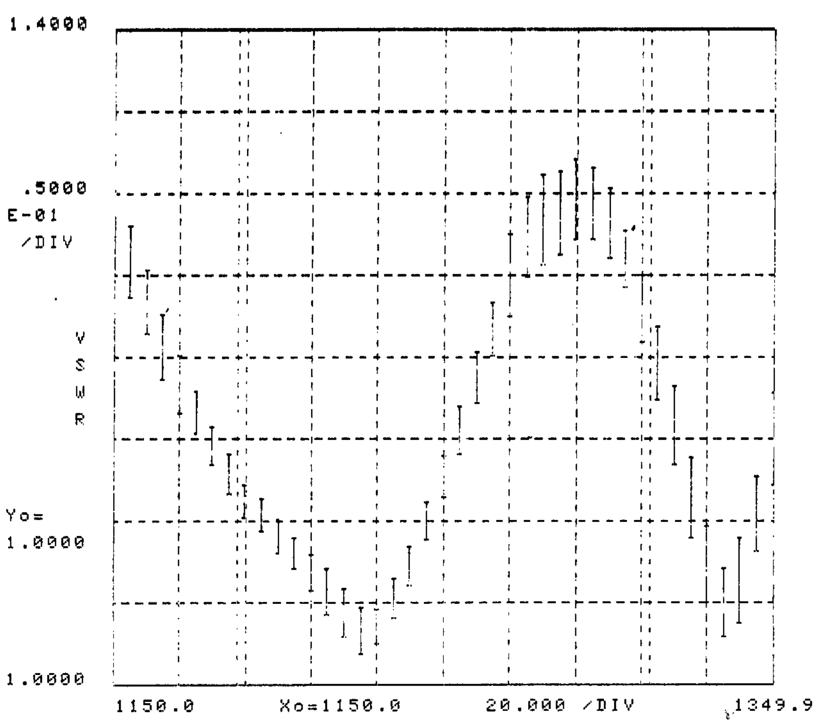
(S) Fig. 47 — Differential phase error spread vs frequency, MA-1, V-Nom



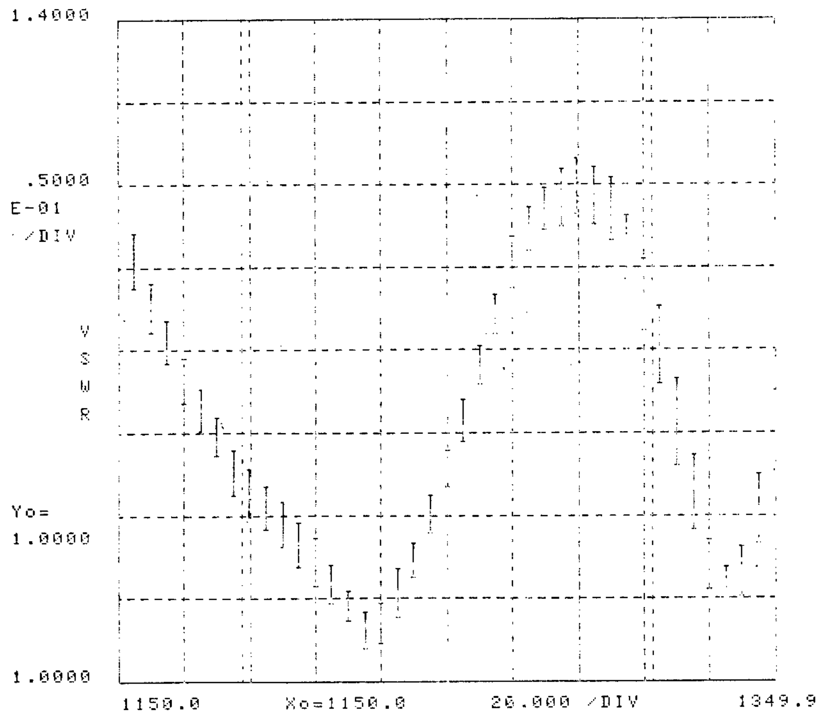
(S) Fig. 48 — Differential phase error spread vs frequency, MA-1, V-High



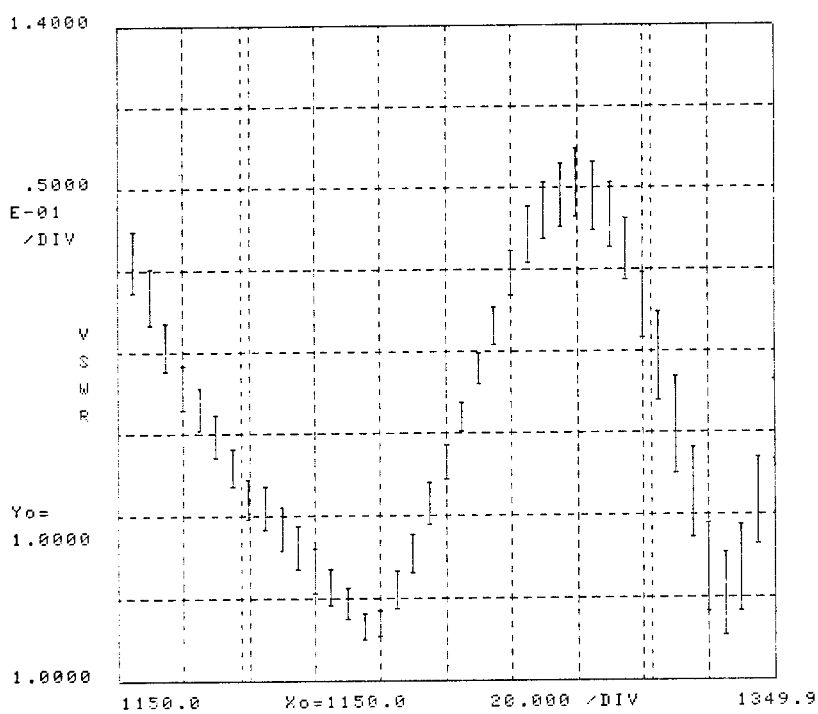
(S) Fig. 49 — Differential phase vs frequency, MA-1, A11-V



(S) Fig. 50 — VSWR spread vs frequency, MA-1, V-Low



(S) Fig. 51 — VSWR spread vs frequency, MA-1, V-Nom



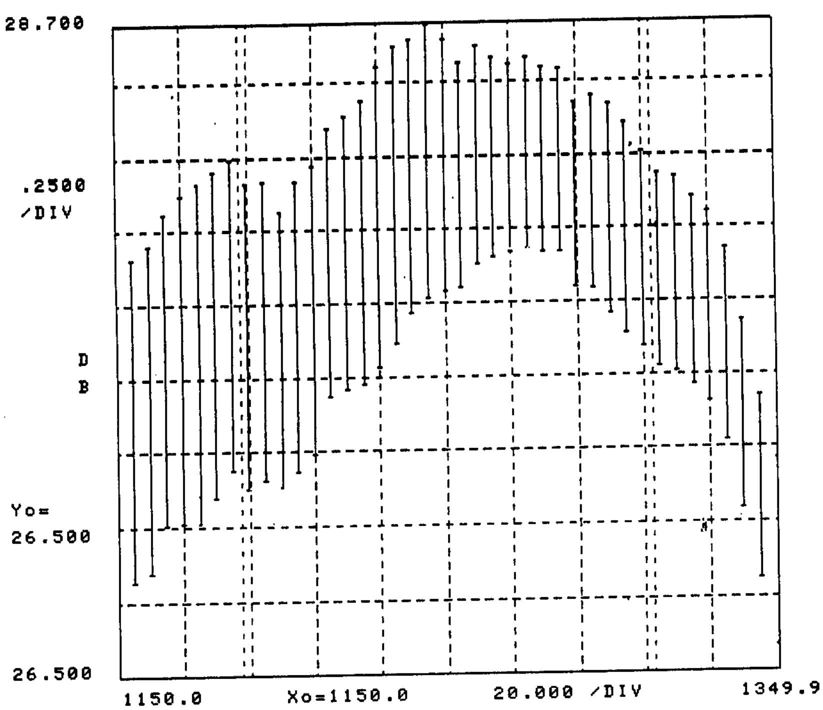
(S) Fig. 52 — VSWR spread vs frequency, MA-1, V-High

(U) The MA-1 receiver exhibited an intermittent failure during the test phase, apparently from a loose internal connection. Tapping the amplifier made connection, at which time it was possible to make measurements. The key to determining that measurements could have validity was that phase was noticeably controllable when the HP analyzer was switched to manual operation and different phase shifts were inserted into the receiver while watching a CRT display. It is felt that, indeed, valid measurements were made on the unit.

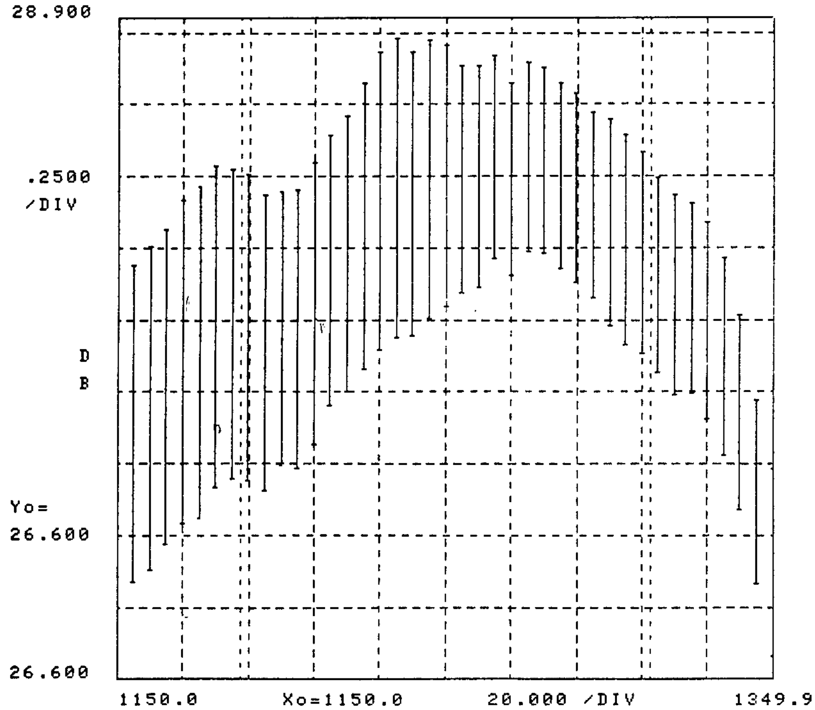
(U) The spread of MA-2 receiver gain vs frequency is shown in Figs. 53, 54, and 55 for low, nominal, and high supply voltages. As for the previously discussed receivers gain varied directly with supply voltage. With respect to MA-1, the MA-2 gain spreads are somewhat smaller per frequency.

(U) As with receiver MA-1, the 1-dB bandwidth specification was not met over all phase states.

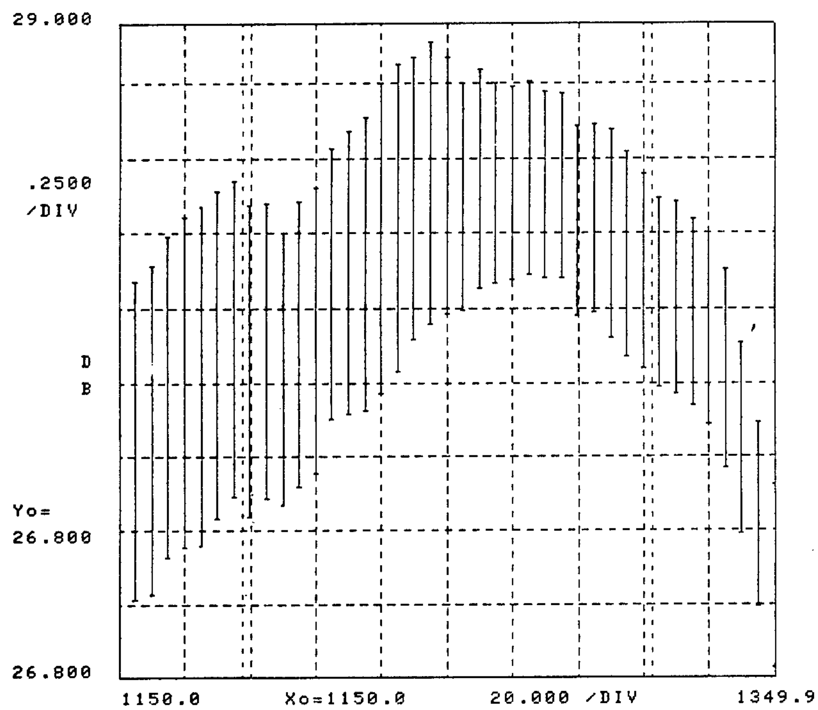
(U) The differential phase error spreads vs frequency, Figs. 56, 57, and 58, showed little change with power supply voltage variations. The differential phase error specification was easily met.



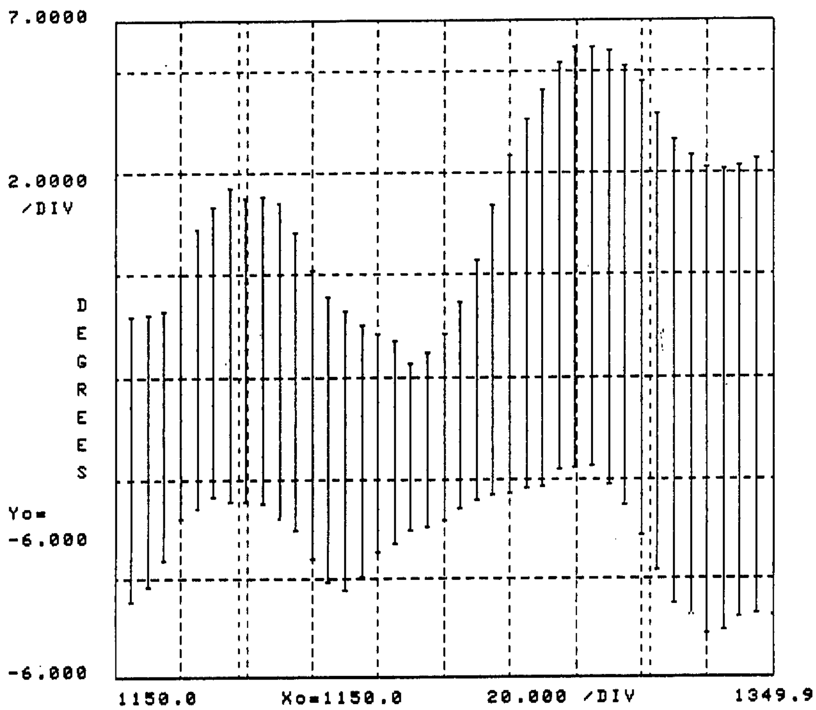
(S) Fig. 53 — Gain spread vs frequency, MA-2, V-Low



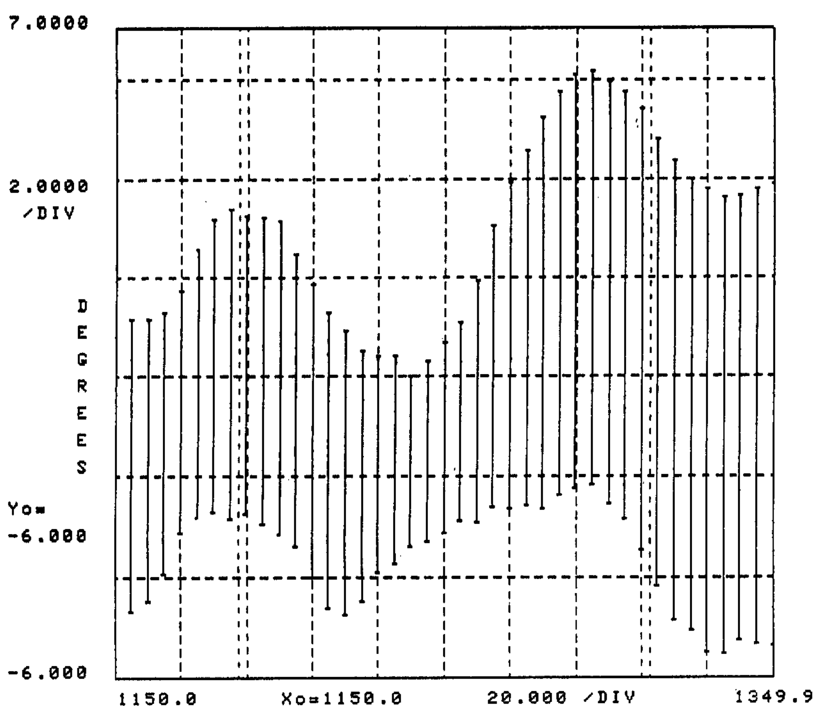
(S) Fig. 54 — Gain spread vs frequency, MA-2, V-Nom



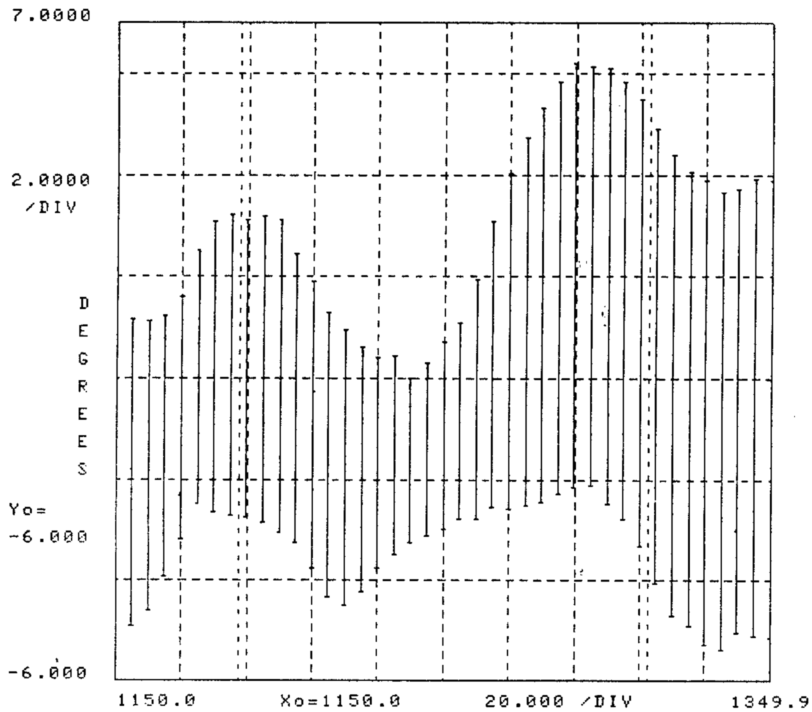
(S) Fig. 55 — Gain spread vs frequency, MA-2, V-High



(S) Fig. 56 — Differential phase error spread vs frequency, MA-2, V-Low



(S) Fig. 57 — Differential phase error spread vs frequency, MA-2, V-Nom



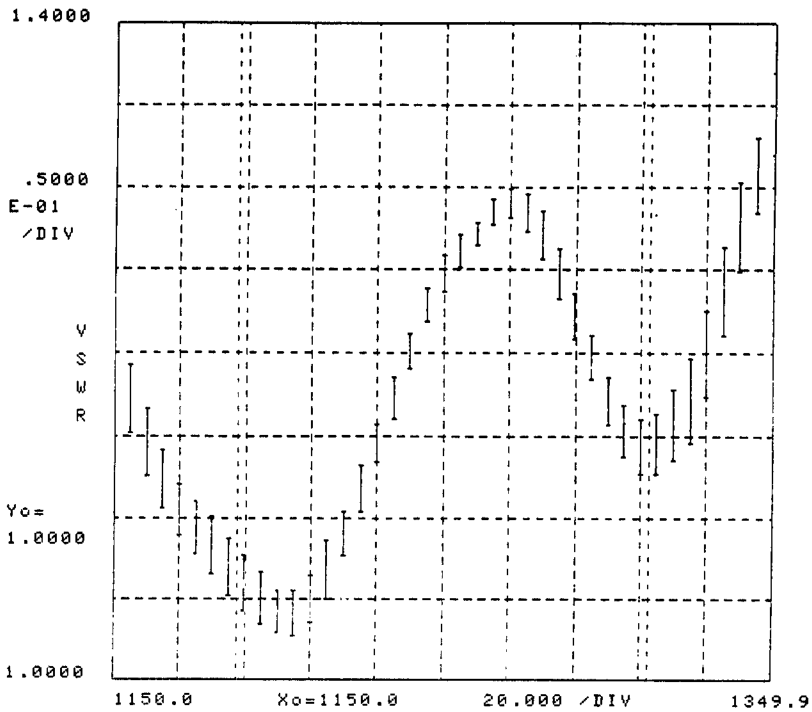
(S) Fig. 58 — Differential phase error spread vs frequency, MA-2, V-High

(U) The VSWR spreads, Figs. 59, 60, and 61, are within 1.4 for the entire test bandwidth. They show small variations with phase change over the test bandwidth, and independence from power supply fluctuations.

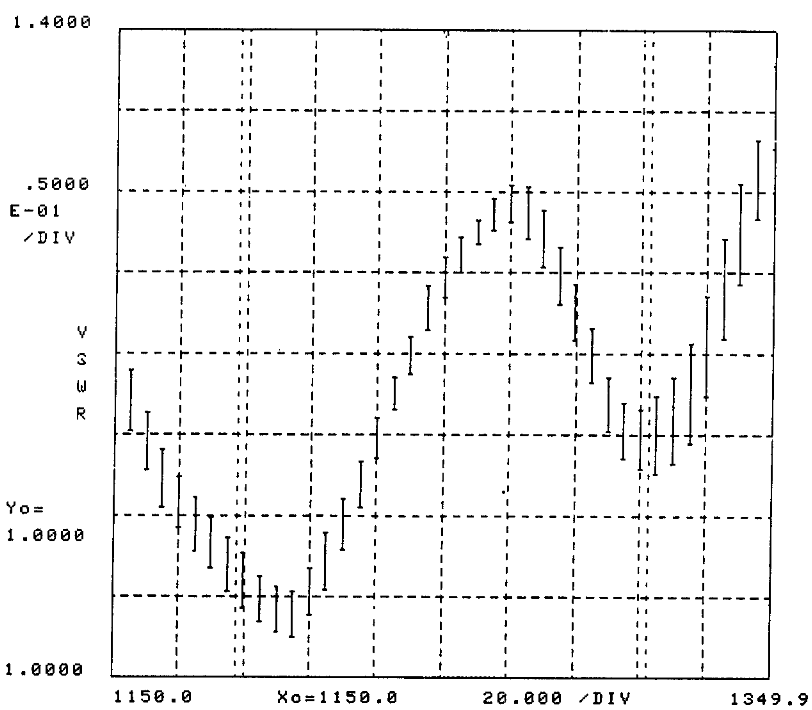
(U) The Westinghouse W-1 receiver showed only a small increase in gain as the power supply voltage went from low to high (Figs. 62, 63, and 64). This is evidently caused by current-regulating circuitry incorporated in the receiver which reduces considerably the sensitivity of the amplifer-to-bias variations. Unfortunately the gain spread per frequency, which is more a function of phase state, caused the bandwidth to be approximately 1.3 dB rather than 1 dB over the specified band.

(U) Figures 65, 66, and 67, the differential phase error spreads for W-1 at low, nominal, and high voltages, show a little variation of phase with power supply voltage changes. The differential phase error is within specification.

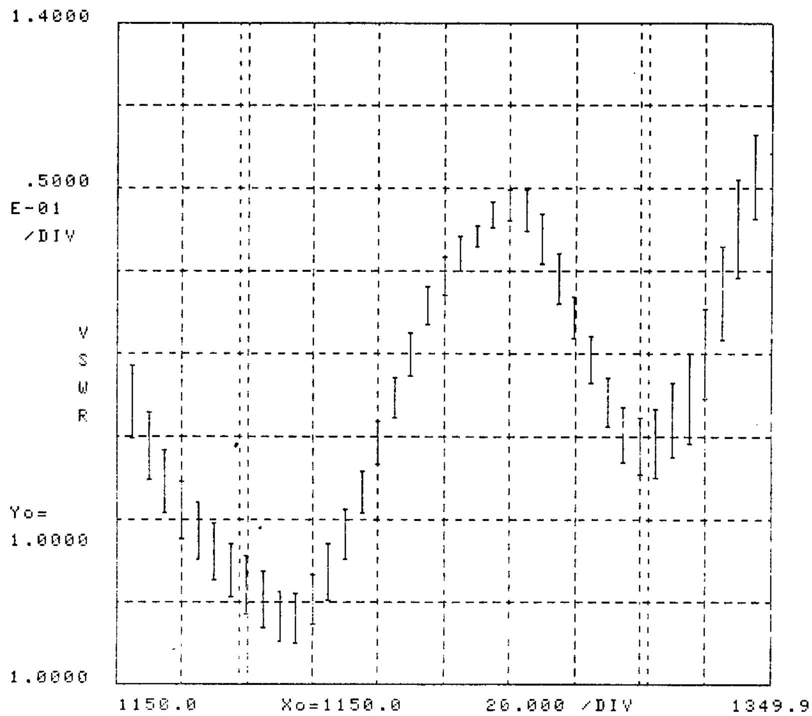
(U) The VSWR spread vs frequency plots, Figs. 68, 69, and 70, show the characteristic independence of VSWR with power supply variations exhibited by all the receivers thus far discussed. All values over the entire test frequency band stayed within the 1.4 limit specified. It is interesting to note the cyclical variation of VSWR with frequency. This is similar to what was seen in the MA VSWR spreads. Since RCA and Westinghouse both used identical circulators while MA used their own design, and the RCA receiver VSWR spreads did not exhibit this characteristic, the circulators are evidently not the cause. It is suspected that the T/R switches and limiters that followed the circulators at the low-noise amplifier inputs caused reflections over the broad band of frequencies.



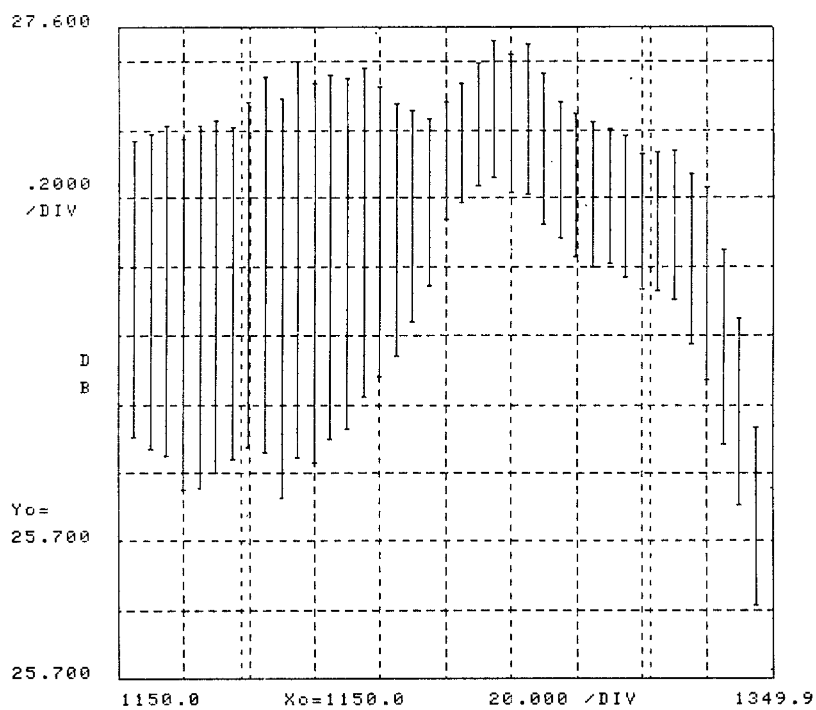
(S) Fig. 59 — VSWR spread vs frequency, MA-2, V-Low



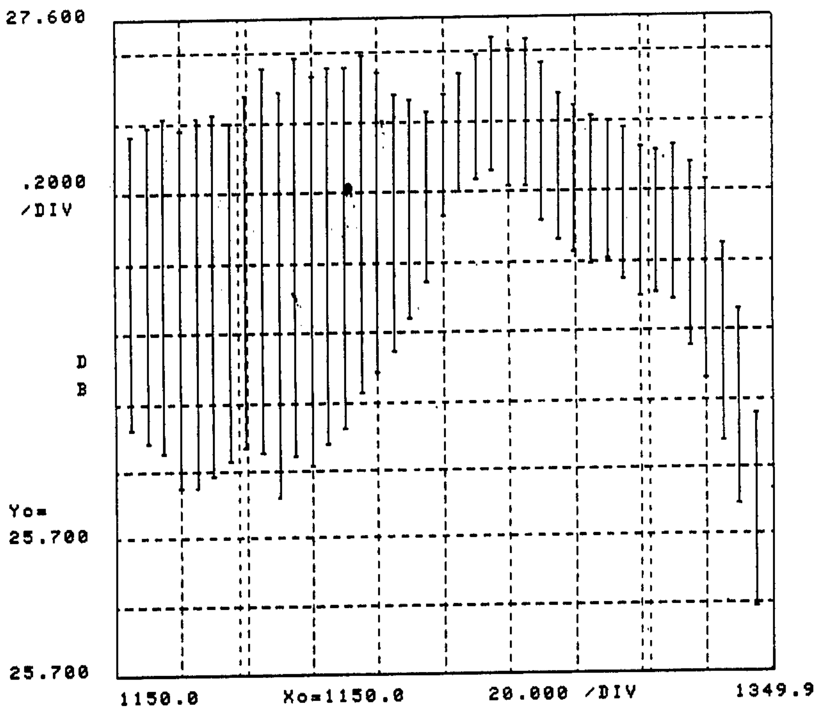
(S) Fig. 60 — VSWR spread vs frequency, MA-2, V-Nom



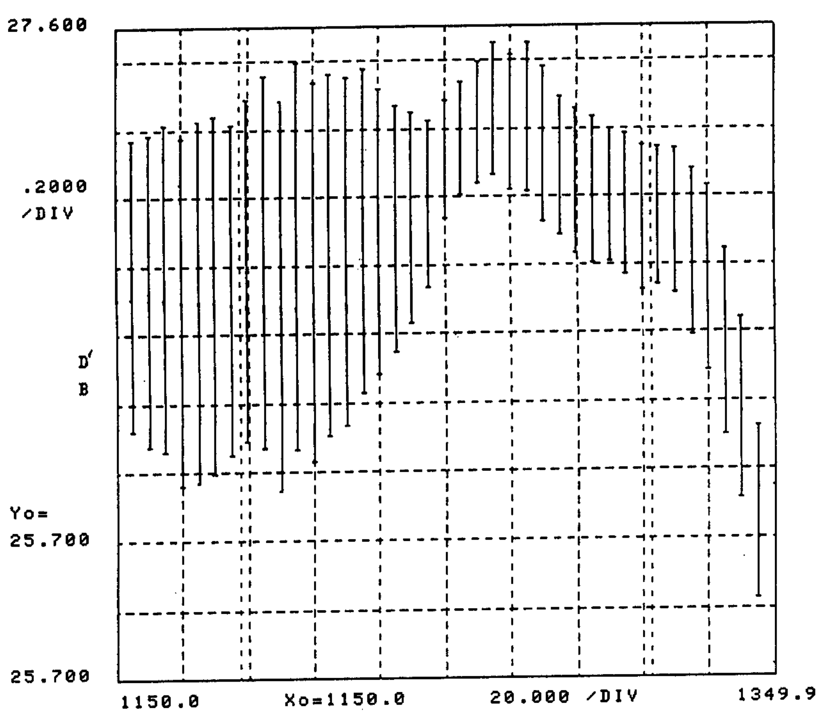
(S) Fig. 61 — VSWR spread vs frequency, MA-2, V-High



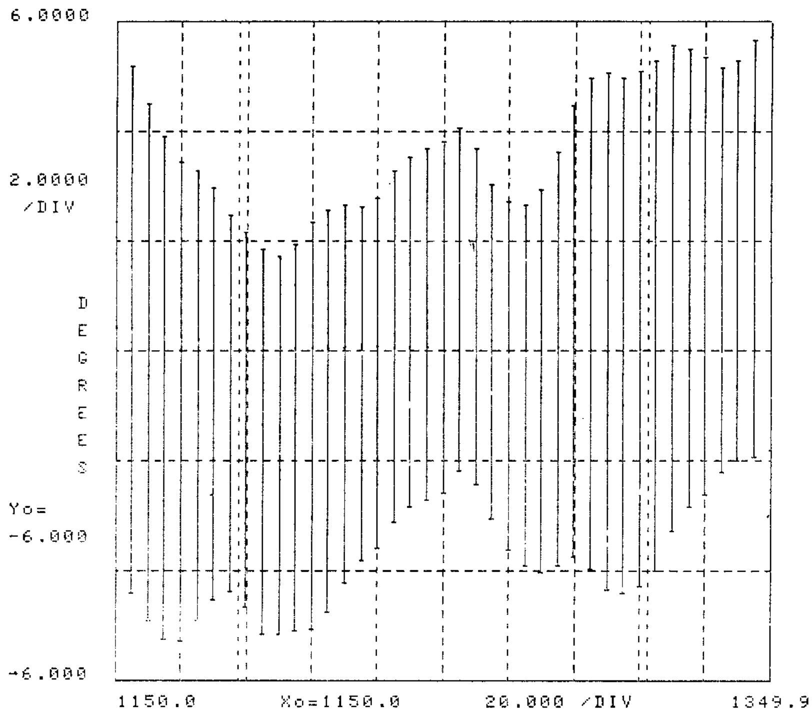
(S) Fig. 62 — Gain spread vs frequency, W-1, V-Low



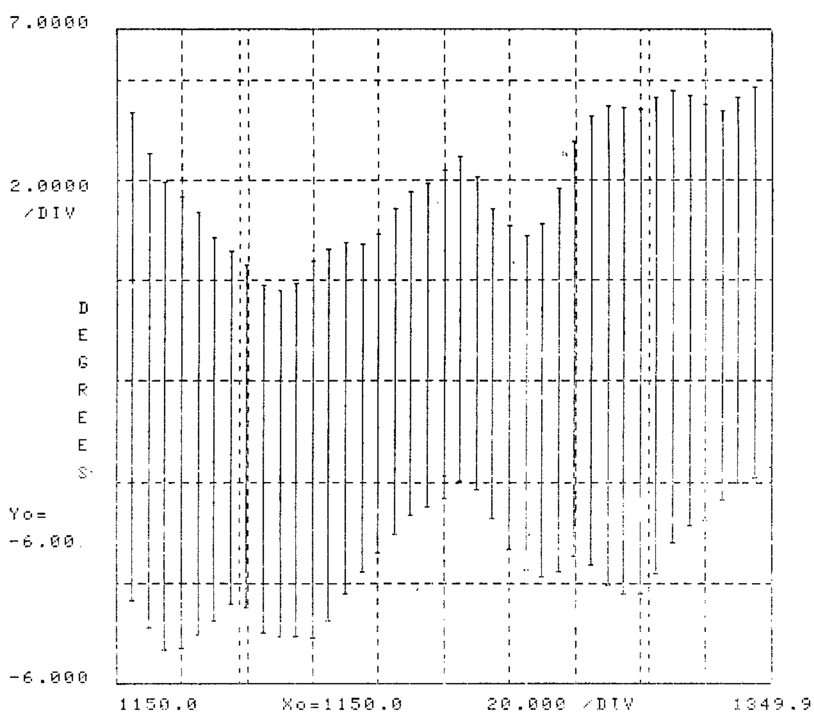
(S) Fig. 63 — Gain spread vs frequency, W-1, V-Nom



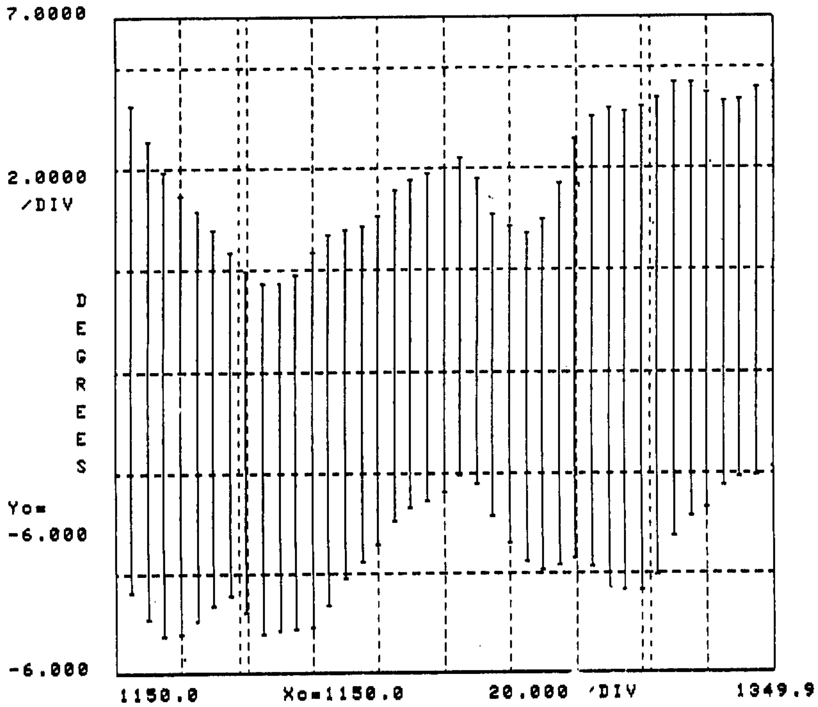
(S) Fig. 64 — Gain spread vs frequency, W-1, V-High



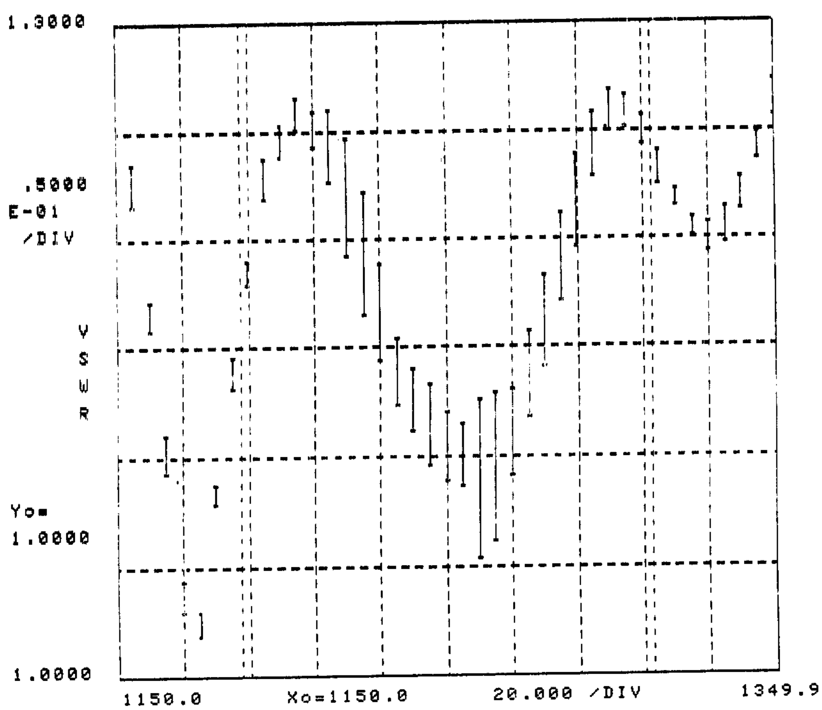
(S) Fig. 65 — Differential phase error spread vs frequency, W-1, V-Low



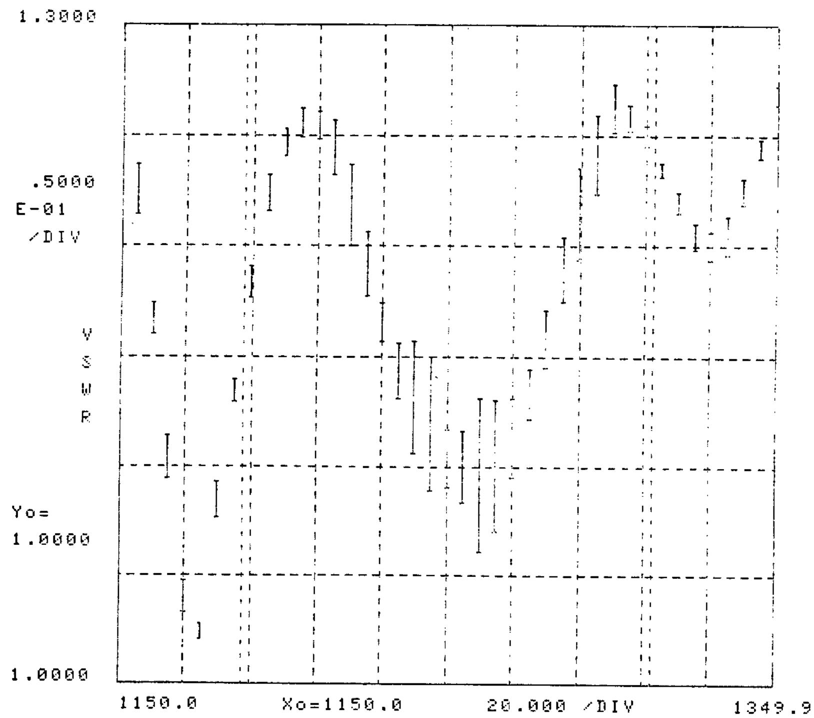
(S) Fig. 66 — Differential phase error spread vs frequency, W-1, V-Nom



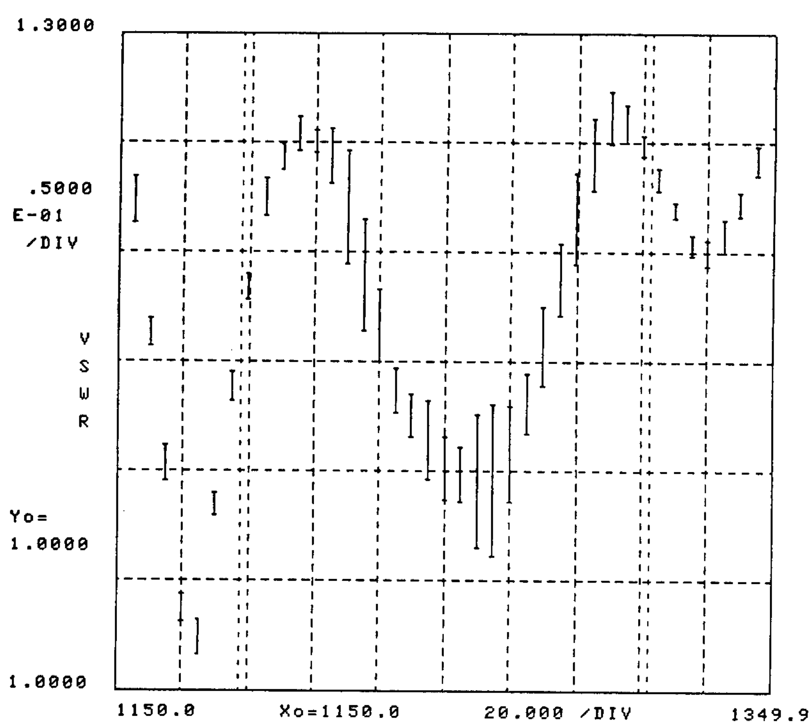
(S) Fig. 67 — Differential phase error spread vs frequency, W-1, V-High



(S) Fig. 68 — VSWR spread vs frequency, W-1, V-Low



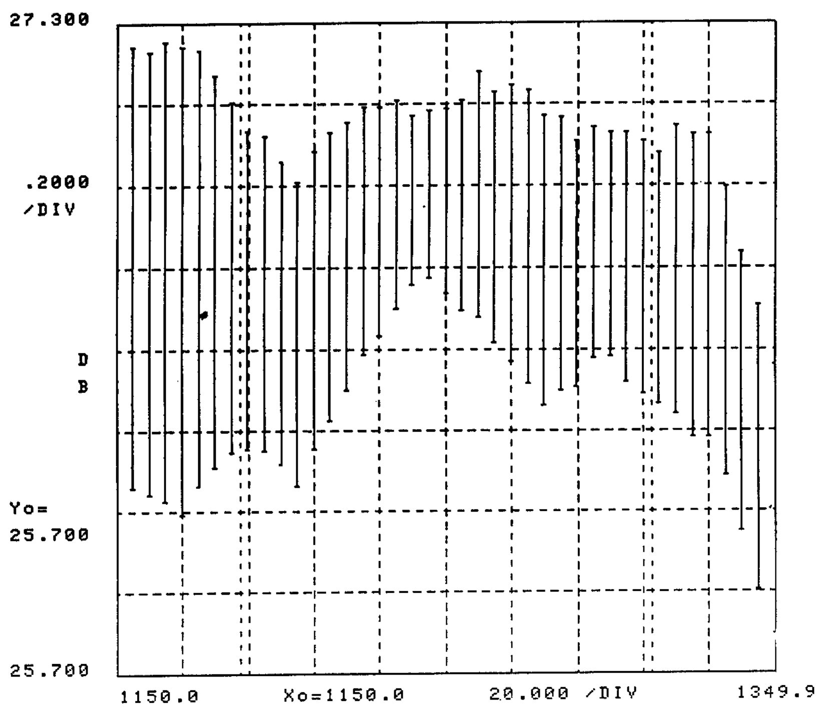
(S) Fig. 69 — VSWR spread vs frequency, W-1, V-Nom



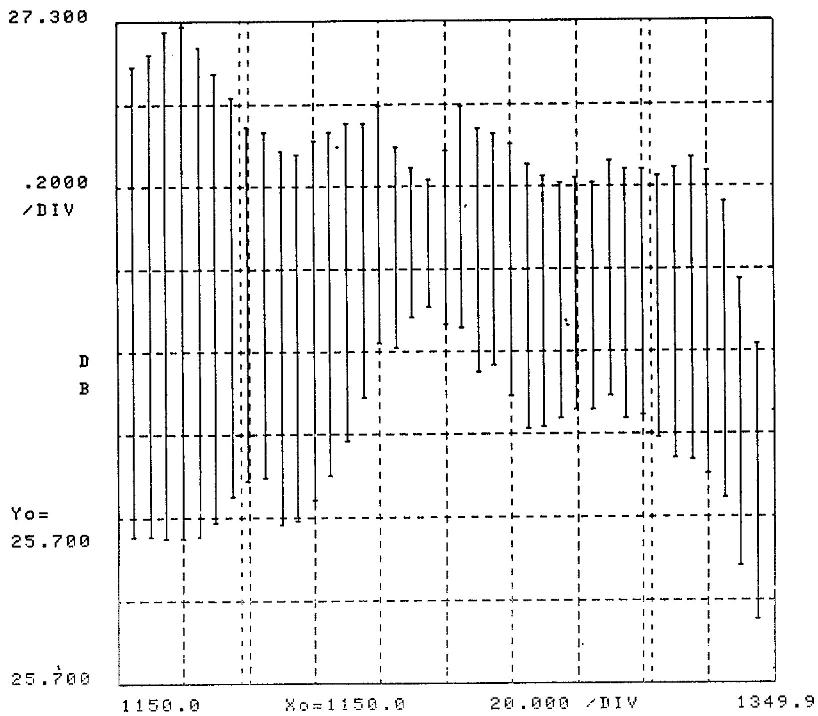
(S) Fig. 70 — VSWR spread vs frequency, W-1, V-High

(U) The gain spread vs frequency plots for W-2, Figs. 71 and 72, show that for low and nominal voltages this receiver meets the 1-dB specification; Fig. 73 for high voltage illustrates approximately a 1.1-dB (specified) bandwidth. However, by the interpretation discussed earlier, the specification had to be met for all phase states and under all specified conditions of power supply variations. The gain spread shown for high voltage appears to be the worst case, since the receiver gain is relatively insensitive to supply voltage changes. Therefore, this unit should be given credit as having met the bandwidth specification.

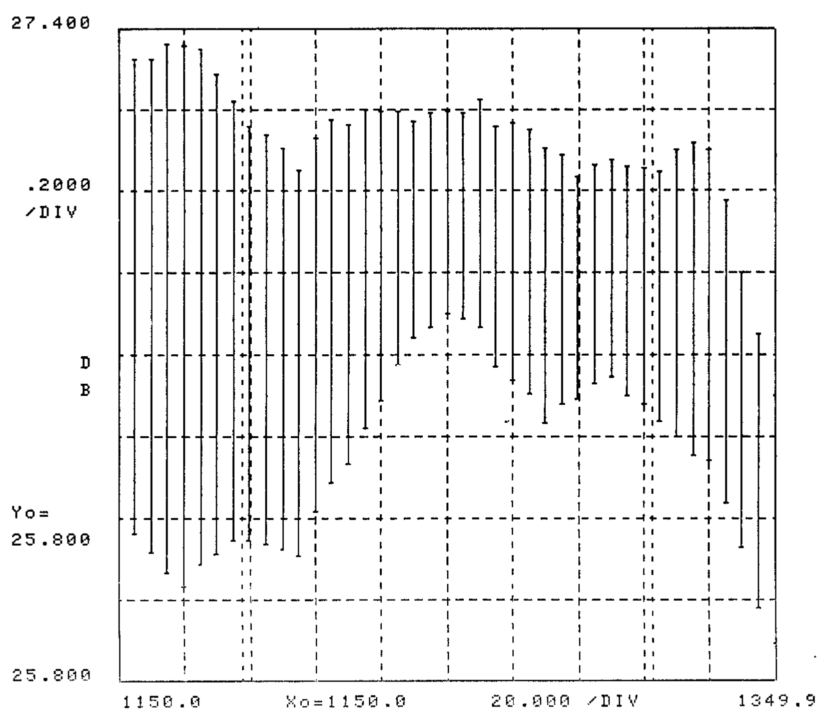
(U) The differential phase error spread vs frequency plots for W-2, Figs. 74, 75, and 76, show receiver conformance to the differential phase error specification. However, as the supply voltage changes, phase changes in the order of 0.7 degrees occur, particularly at and slightly above the center frequency. Visual examination makes the phase differences between plots on Figs. 74 and 76 appear greater, but this is caused by a slight difference in ordinate dimensions (-6 vs -5 degrees).



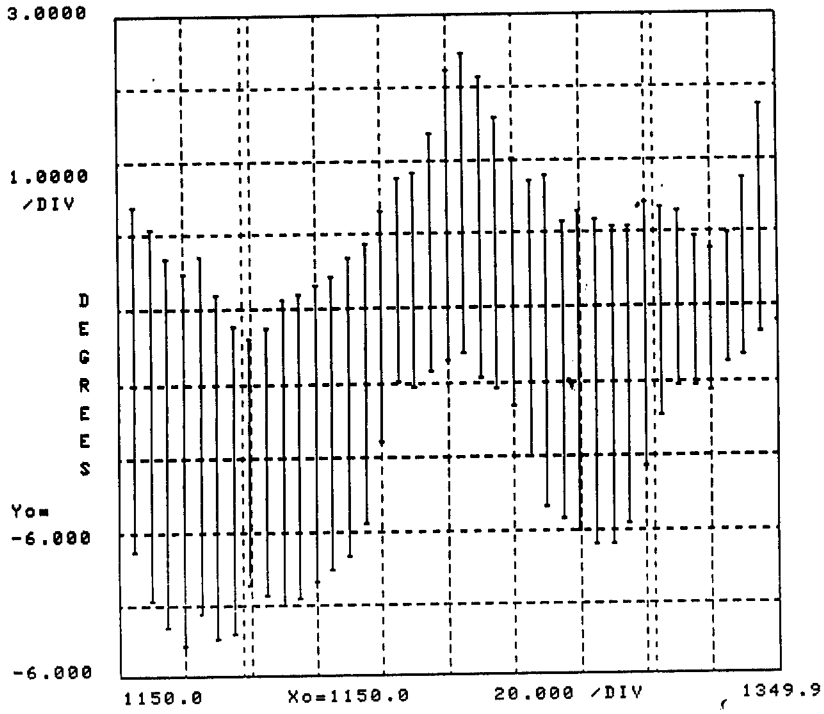
(S) Fig. 71 — Gain spread vs frequency, W-2, V-Low



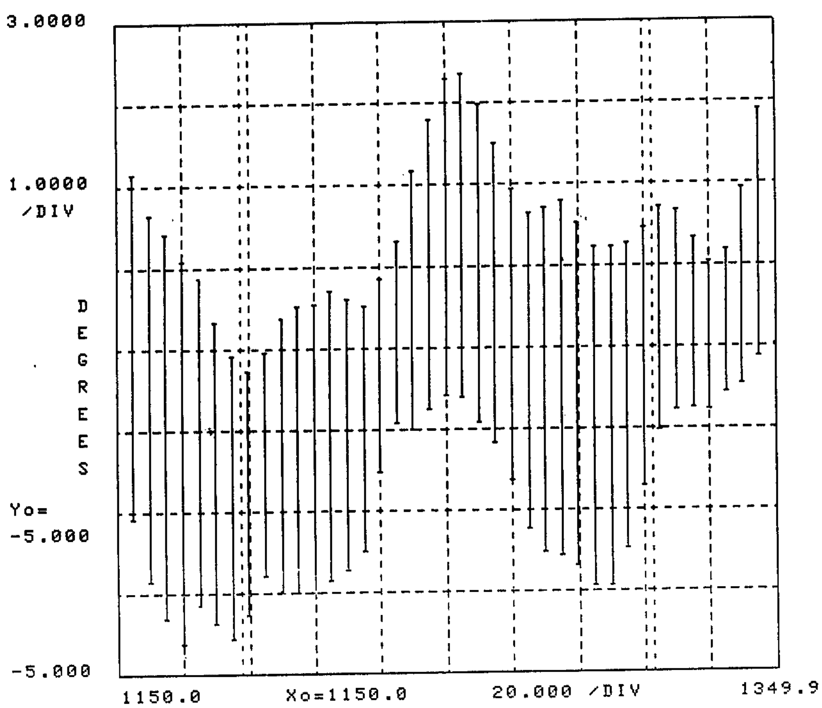
(S) Fig. 72 — Gain spread vs frequency, W-2, V-Nom



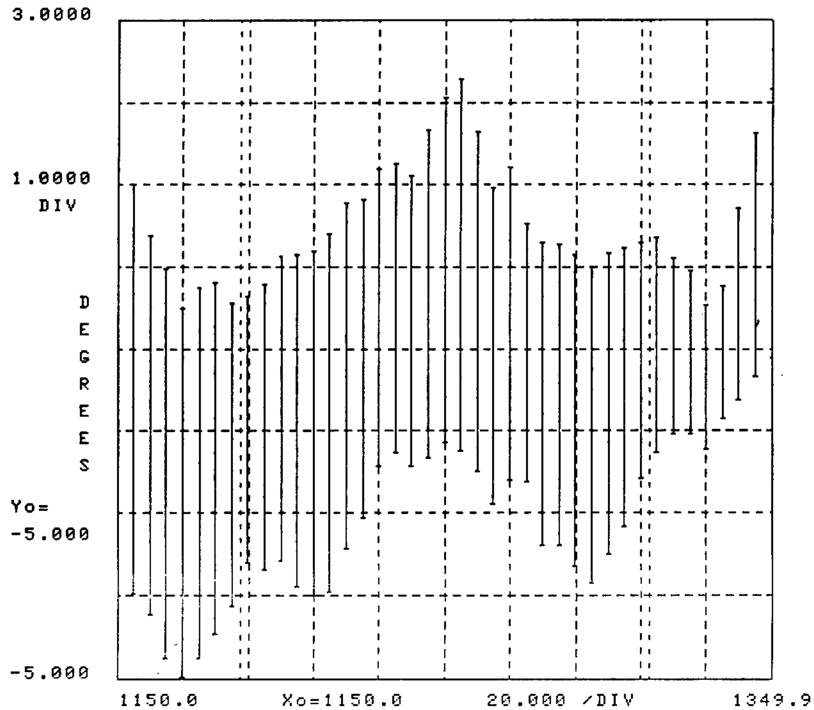
(S) Fig. 73 — Gain spread vs frequency, W-2, V-High



(S) Fig. 74 — Differential phase error spread vs frequency, W-2, V-Low



(S) Fig. 75 — Differential phase error spread vs frequency, W-2, V-Nom



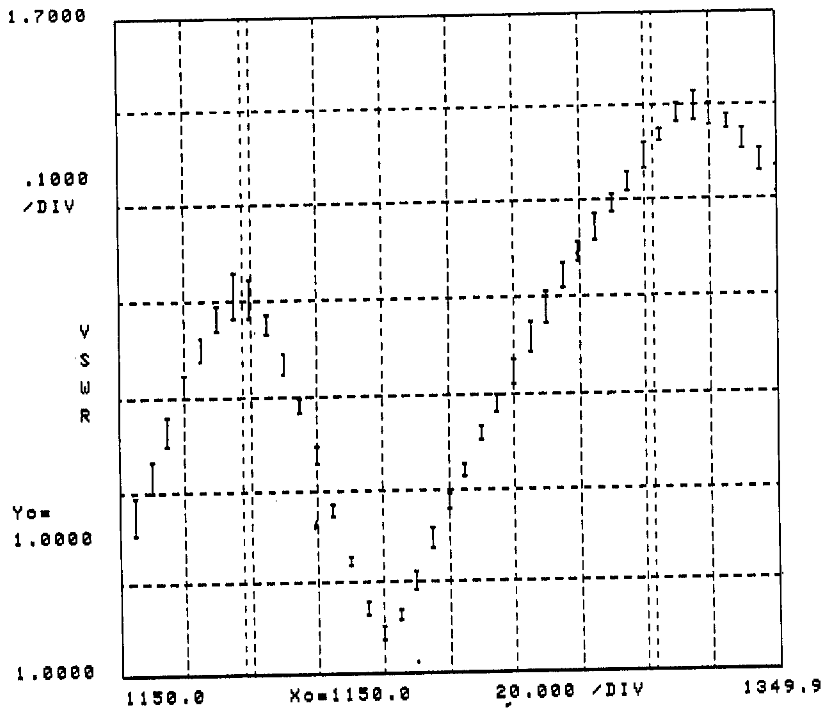
(S) Fig. 76 — Differential phase error spread vs frequency, W-2, V-High

(U) The plots of VSWR spread vs frequency are shown in Figs. 77, 78, and 79 for low, nominal, and high voltages. The cyclical nature of the VSWR with frequency evinced by the W-1 receiver is also evident here. In addition, the 1.4 specification is exceeded both at the low end and some 30 MHz from the high end of the specified band. Although this out-of-specification condition appears to be worse for the W-1 than for all other receivers tested, it nevertheless conforms to the pattern of independence from supply-voltage variations.

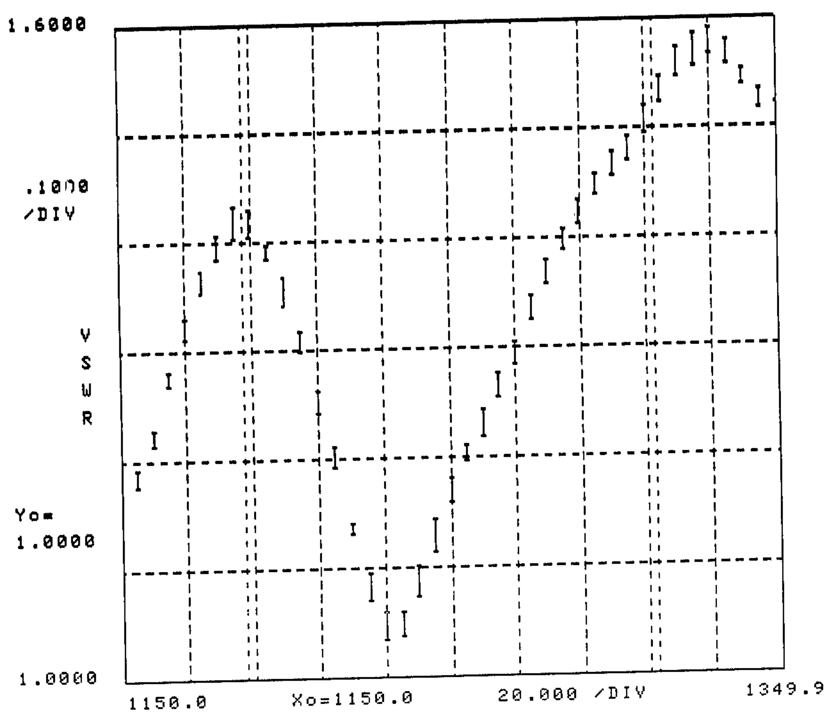
(U) The results of varying the supply voltages are, briefly, the following. The gains of the RCA and MA receivers varied directly as the supply voltage. Only the Westinghouse receivers maintained constant gain characteristics. Most receivers could not meet the 1-dB bandwidth requirement for all phase states and power supply variations. Only one unit, a Westinghouse receiver, showed up well.

(U) Differential phase characteristics for all receivers were quite good. There were, however, some small phase variations (up to 2 degrees) with supply voltage. It is possible that the change shown for the MA-1 receiver was due to the intermittent loose connection in the module known to exist during testing.

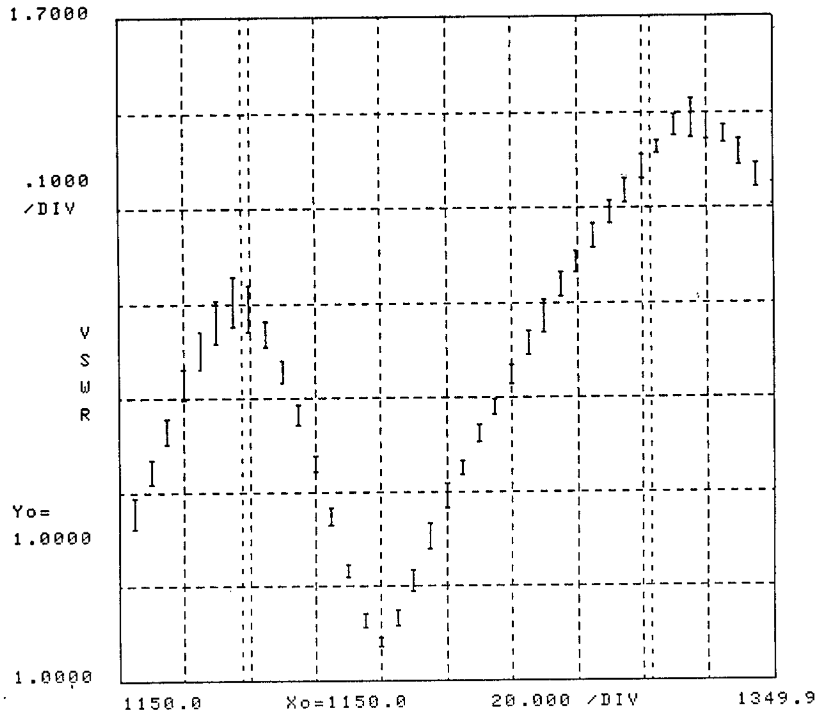
(U) Overall, VSWR characteristics were good for all units except the W-2 receiver. Not only were they well within the specification limits, but also were remarkably immune to power supply variations.



(S) Fig. 77 — VSWR spread vs frequency, W-2, V-Low



(S) Fig. 78 — VSWR spread vs frequency, W-2, V-Nom



(S) Fig. 79 — VSWR spread vs frequency, W-2, V-High

(U) A comparison of some other receiver characteristics is shown in Table 8. There it can be seen that the equivalent lengths per contractor type compare well from one unit to another. It is interesting to note that these measurements (by NRL) show MA and Westinghouse module receivers almost alike in length and RCA's differing from them by some 60 cm, even though RCA and Westinghouse used similar circulators and MA's was different from both.

(U) The insertion phase errors (IPE) (rms and peak) were obtained by taking best-fit linear lines through zero phase state (reference) data and determining the deviations of the actual data compared to the linear line.

(U) The differential phase errors (DPE) were determined as discussed previously, but those listed are for all phase states rather than an individual one.

(U) For each module receiver type, values could be combined to give the overall error E

$$\text{RMS E per unit} = \left[\frac{(\text{RMS}_{\text{IPE}})^2 + (\text{RMS}_{\text{DPE}})^2}{2}\right]^{1/2},$$

Table 8
Receiver Characteristics

Receiver	Airline (cm)			Offset (degrees)			Insertion Phase Error (degrees rms)			Insertion Phase Error (degrees peak)			Reverse Isolation Transmitter Receiver		Differential Phase Error (degrees rms)			Differential Phase Error (degrees peak)		
	low	nominal	high	low	nominal	high	low	nominal	high	low	nominal	high	nominal	nominal	low	nominal	high	low	nominal	high
RCA-1	148.09	148.17	149.06	11.89	9.01	18.33	0.87	0.89	0.83	-1.67	-1.68	-1.64	OK	OK	2.90	3.02	3.05	-7.18	-7.43	-7.35
RCA-2	149.85	150.48	150.84	45.82	57.49	52.17	0.90	0.79	0.80	-2.12	-1.94	-1.91	-1.75[a]	OK	3.24	3.02	3.25	-8.02	-7.89	-8.23
MA-1	211.85	211.52	211.30	142.44	138.46	134.36	1.27	1.38	1.31	-3.60	--3.80	-3.42	OK	OK	2.55	3.08	2.68	7.26	7.88	7.28
MA-2	209.21	209.21	209.00	112.56	112.67	109.32	0.84	0.85	0.84	-2.27	-2.20	-2.29	OK	OK	2.12	2.14	2.16	6.20	6.48	6.17
W-1	211.88	211.78	211.83	98.71	97.48	97.77	2.40	2.41	2.46	-5.15	-5.13	-5.29	OK	b	2.20	2.25	2.22	-5.16	5.49	5.23
W-2	202.28	202.5	203.07	7.28	11.07	16.86	1.86	1.64	1.51	+3.14	-2.72	-2.56	OK	c	1.96	1.76	1.61	-5.00	-4.27	-3.98

[a]General frequencies 1.75 dB below specification.
[b]Two frequencies 0.5-1.75 dB below specification.
[c]Greater than 9 dB below specification.

which is one of the steps necessary for the evaluation of module receivers in terms of a system specification. Such a specification would be used for a phased array encompassing many receivers.

(U) Transmitter and receiver reverse isolations in most cases were below the specified level. There were some deviations as noted, and one unit (W-2 receiver) appeared very much out of specification.

TRANSMITTERS

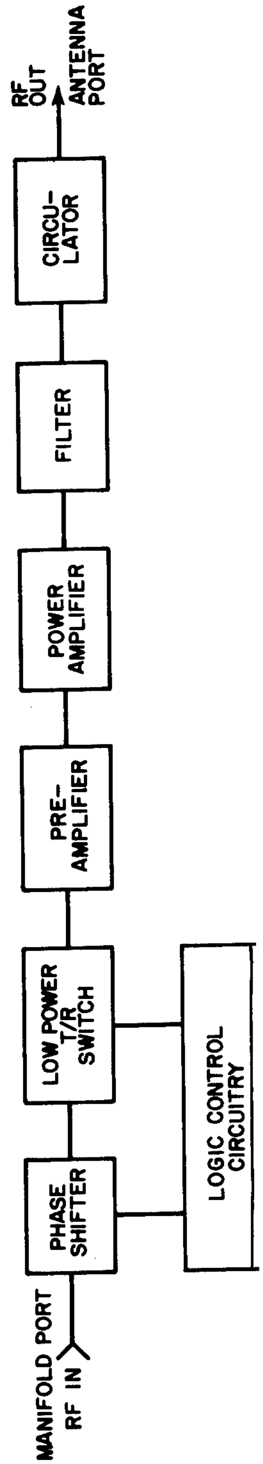
Signal Flow

(U) A generalized block diagram of a transmitter is shown in Fig. 80. The transmitter begins at the manifold port of the module, which is the entry point for RF pulses. Signal flow proceeds through the phase shifter and a low-power T/R switch, both of which are controlled by logic contained in a flatpack. The logic control circuitry itself receives digital inputs from a source external to the module. For the engineering models of the modules, each contractor provided a "diddle" box that had electronic or mechanical provisions for generating digital commands for the module. The position (state) of the T/R switch controls the direction of signal flow to the transmitter preamplifier (or from the receiver). The preamplifier is usually a Class-A-operated stage that is sometimes digitally pulse modulated (an energy-conserving measure). The power amplifier that follows consists of four to six parallel Class-C-operated transistor stages. A low-pass filter (if incorporated) follows the power amplifier, after which signals pass through a circulator to the antenna port, the exit from the module.

Phase Shifter and Low-Power T/R Switch

(U) All modules used 4-bit digitally controlled, diode-switched phase shifters. These permitted the generation of 16 phase states in steps of 22.5 degrees. Figure 81 is a schematic of a typical phase shifter that contains two phase bits capable of four possible phase states. In operation, a straight path from points 1 and 2 is provided for the RF which, in the zero phase state, passes through conductive strips S, and a basic phase shift results. The two phase shifter elements ϕ_1 and ϕ_2 are also conductive strips of different lengths that can be switched into the RF path in place of the S strip opposite. (In the 4-bit unit there would be four such strips representing 22.5, 45, 90, and 180 degrees.) In addition to the desired phase length, enough length must be provided to compensate for the phase length of an S strip; i.e., if S were 2 degrees long and ϕ_1 were to provide a 90-degree phase shift, the strip comprising ϕ_1 would actually be 92 degrees long.

(U) Digital control of the diodes of the phase shifter is exercised by connecting flatpack logic elements to diode cathodes A, B, E, and F such that A is low while F is high, B is low while E is high, or vice versa. The diode anodes are connected to a low positive voltage. The diodes are energized in pairs; CR1, CR2, and CR5, CR6 for the through-signal cases (zero phase shift), or CR3, CR4 and CR7, CR8 to introduce phase shifts ϕ_1 and ϕ_2, respectively. Required logic states for desired phase states for the 2-bit phase shifter are



(U) Fig. 80 — General, transmitter circuit

shown in Table 9; the 4-bit phase shifter as used in the modules would have 16 phase states.

(U) The low-power T/R switch composed of diodes CR9 and CR10 is controlled in the same manner as the phase shifter. Points C and D are connected to flatpack logic elements so that if C is low, D is high, or vice versa. The diode anodes are connected to a low positive voltage. In this manner either the receiver signal path or the transmitter signal path must be energized, unless there is a malfunction.

Transmitter Design Approaches

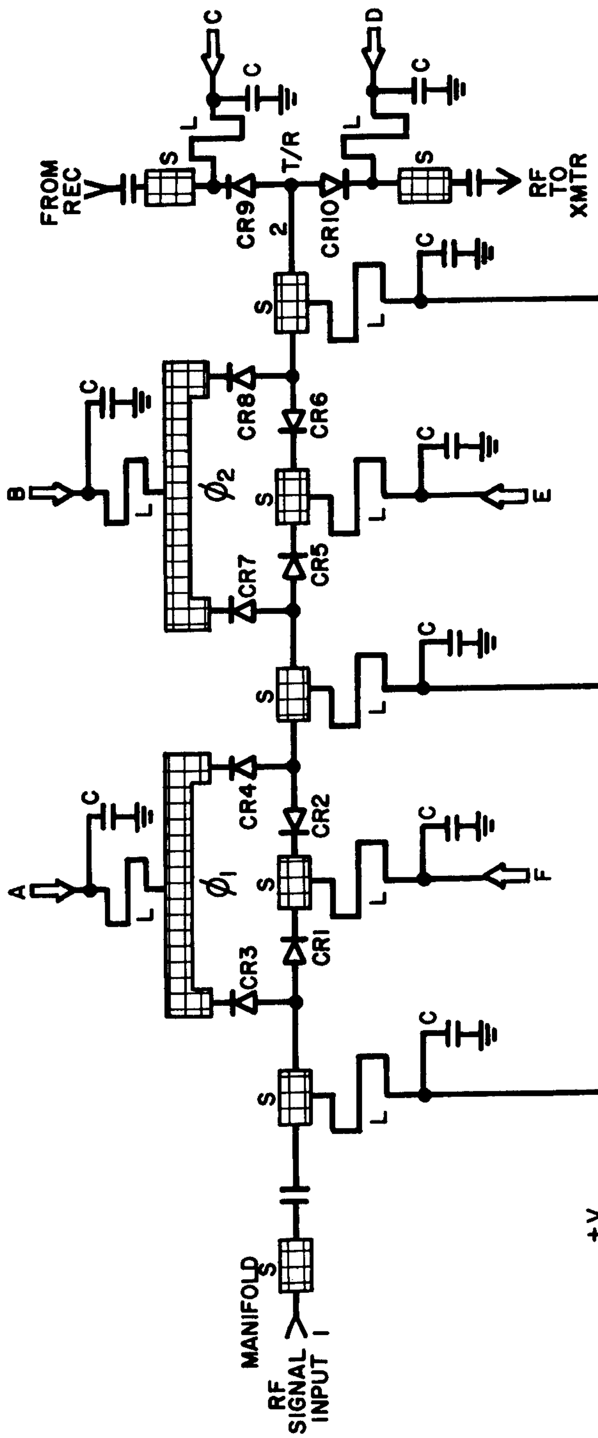
Microwave Associates Transmitter

(U) The transmitter produced by Microwave Associates, in order to achieve the required levels of efficiency, power output, gain, and bandwidth, was configured to utilize Microwave Semiconductor (MSC) devices throughout. It used MSC-3000 series devices for all stages except the output which uses the newly developed MSC 1330. The amplifier evolved into the form shown in Fig. 82. Figure 83 shows the MA transmitter.

(U) The amplifier consists of four cascaded stages, the last two of which contain hybrid coupled devices. The first stage is an MSC 80064, which is an MSC 3000 in a common-emitter configuration. It is biased Class A so as to provide sufficient gain at low input drive levels. Its bias circuitry is capable of being pulsed on some time (such as 40 μsec) prior to the RF pulse and turned off (approximately 20 μsec) after the RF pulse to minimize standby dissipation. The second stage is an MSC 80117, which is physically half of an MSC 3003. This device was used instead of the standard MSC 3001 and MSC 3003 devices because the MSC 3001 could not provide enough power to drive the following stage; on the other hand, while the MSC 3003 had the capability of supplying enough output power, it did not have sufficient power gain. The third stage consists of a pair of (high-gain) MSC 3005 devices that are driven from the output ports of a 3-dB hybrid coupler. The fourth and final stage consists of two pairs of hybrid-coupled MSC 1330s whose outputs are combined in a final 3-dB coupler.

(U) The output filter, a 3-pole low-pass Chebyshev design, is employed to reduce the second harmonics to below 50 dB. All stages except the first are operated Class C and therefore require relatively little standby power. The nominal voltage on the Class C stages was chosen to be 31 V DC, but subsequent tests showed that by varying this voltage, the best compromises among power, efficiency, and phase performance could be obtained.

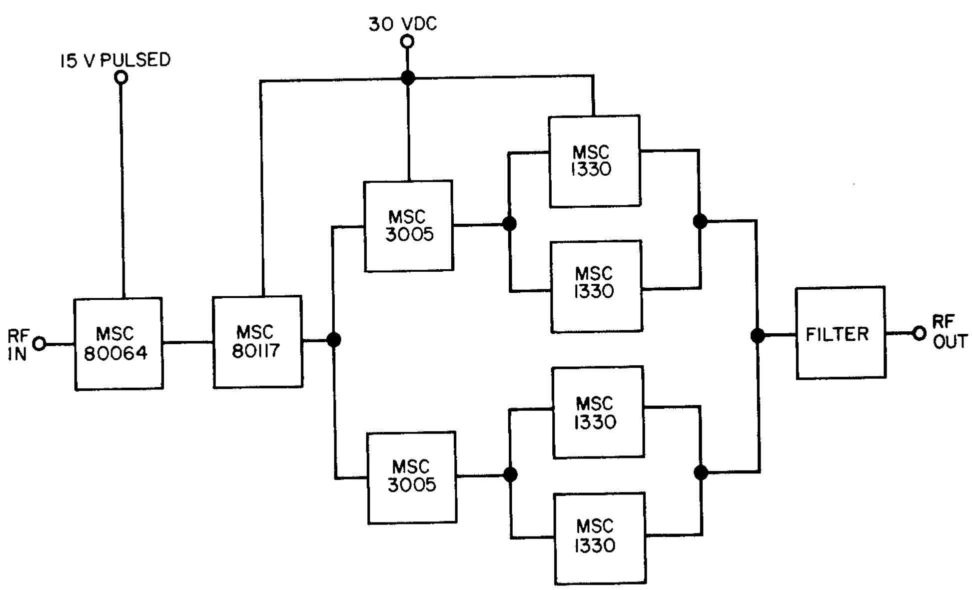
(U) All circuits are constructed on a 0.010-in. Al_2O_3 chrome-gold metalized substrate except for the couplers which are on 0.025-in. substrates. All substrates and devices were soldered onto a gold-plated aluminum carrier with an indium-loaded solder to minimize gold "leaching." The pallet measures 4.4 in. by 3.9 in. by 0.062 in. maximum and weights no more than 4 oz.



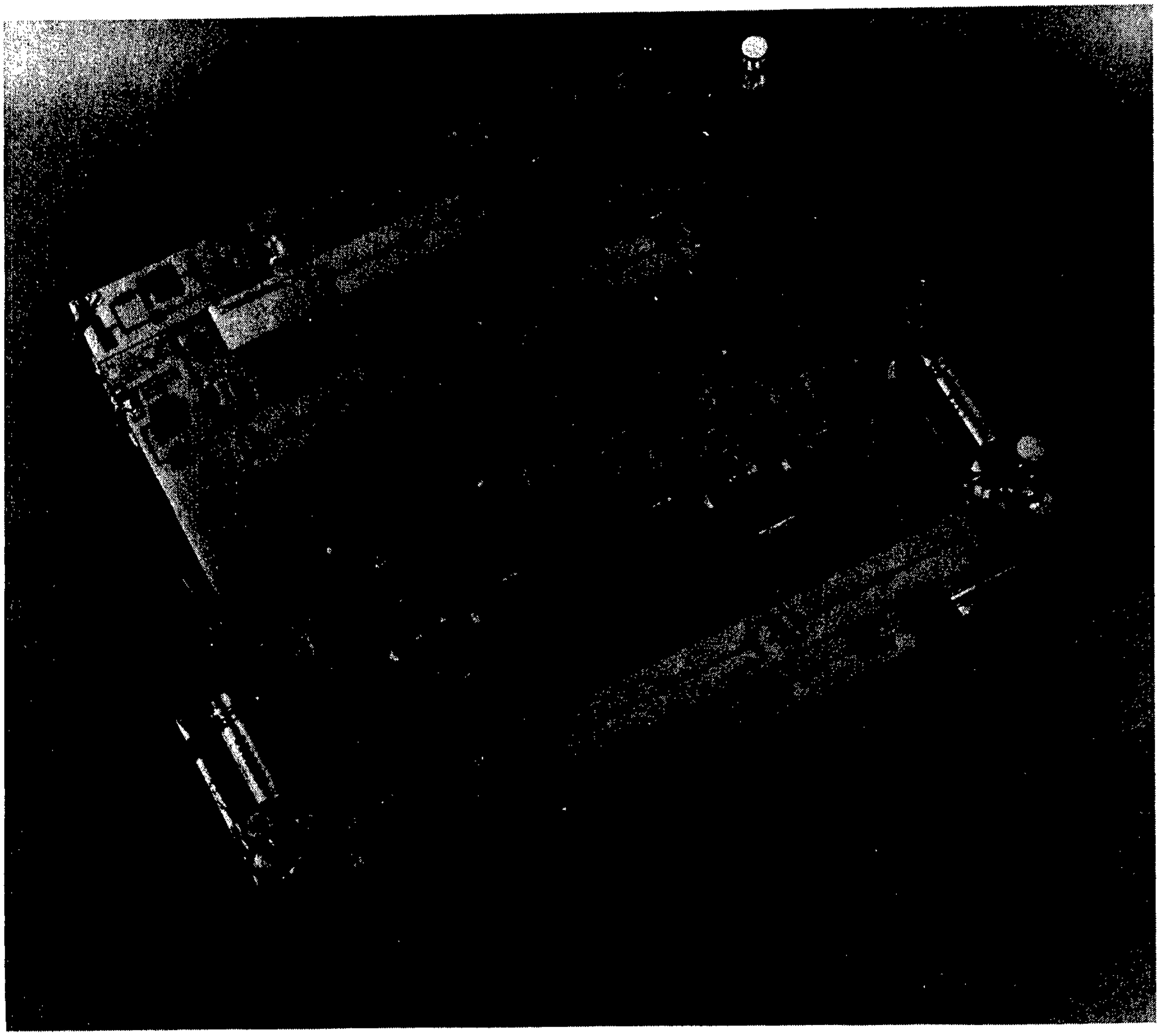
(U) Fig. 81 — Phase shifter

(U) Table 9
Logic State vs Phase Shift

Logic States				Phase State
A	B	E	F	
High	High	Low	Low	ϕ_0
Low	High	Low	High	ϕ_1
High	Low	High	Low	ϕ_2
Low	Low	High	High	$\phi_1 + \phi_2$



(U) Fig. 82 — MA power amplifier



(U) Fig. 83 — MA transmitter

(U) After being assembled, the engineering models were subjected to temperature baking and cycling, after being tuned by removing metalized areas or adding silver paint. Several tuning iterations were performed to get specified operation over the required temperature range. The tuning changes, with their concomitant heating and reheating operations, degraded the amplifier performance by lowering circuit Q. This was apparently due to gold leaching which occurred despite the use of indium-loaded solder. Engineering model 1 (EM-1) developed so many assembly problems that except for the devices it was completely rebuilt. This fact, coupled with the fewer tuning changes required in the rebuilt amplifier, was most likely the reason for a significant improvement in performance of the rebuilt unit over the original one. It is very probable that rebuilding engineering model 2 (EM-2) would have also improved its performance, but time did not allow it; consequently, its performance was slightly worse than EM-1R.

(U) Before final assembly, both engineering models were tested in a prototype module housing and were tuned with their respective circulators in position. This was done to simulate as closely as possible the actual conditions under which the amplifiers would be operating.

Performance Tests

(S) Tests of the engineering models were performed at the MSC facility to ascertain power output and efficiency over the specified band. The results of tests on MA-1 are listed in Tables 10 and 11. Note that the output powers shown are referred back to the output cable of the amplifier, and hence do not include circulator losses. In all cases F_C is 1250 MHz, pulse width and duty cycle are 100 μsec and 1%, respectively. The results of similar tests on MA-2 are listed in Tables 12 and 13 for similar conditions.

(U) Table 10
MA-1 Power
Output vs Frequency at Nominal DC and RF Power Inputs

Frequency (MHz)	Power Output (W)		
	+25°C	T_L	T_H
F_C-70	141	111	130
F_C-60	151	130	135
F_C-50	157	142	140
F_C-40	162	150	143
F_C-30	165	156	148
F_C-20	168	162	151
F_C-10	168	167	155
F_C	168	170	153
F_C+10	165	170	145
F_C+20	162	168	140
F_C+30	159	167	148
F_C+40	155	160	136
F_C+50	151	159	131
F_C+60	144	152	122

(U) Table 11
MA-1 Power Output and Efficiency vs Frequency at High and Low Supply Voltages and High and Low RF Inputs

Frequency (MHz)	P_{in} (mW)	P_{out} (W)	V_1 (V DC)	V_2 (V DC)	I_2 (MA)	Efficiency (%)	Temperature (°C)
F_L	28	143	14.7	30.4	123	38.2	+25
F_C	28	160	14.7	30.4	128	41.3	+25
F_H	28	136	14.7	30.4	117	38.4	+25
F_L	45	143	14.7	30.4	123	38.2	+25
F_C	45	161	14.7	30.4	130	40.9	+25
F_H	45	136	14.7	30.4	117	38.4	+25
F_L	28	155	15.3	31.6	127	38.7	+25
F_C	28	173	15.3	31.6	135	40.6	+25
F_H	28	147	15.3	31.6	123	37.8	+25
F_L	45	152	15.3	31.6	127	37.9	+25
F_C	45	173	15.3	31.6	135	40.6	+25
F_H	45	147	15.3	31.6	123	37.8	+25
F_L	28	115	14.7	30.4	112	33.9	T_L
F_C	28	147	14.7	30.4	120	40.2	T_L
F_H	28	136	14.7	30.4	118	38.1	T_L
F_L	45	121	14.7	30.4	117	33.9	T_L
F_C	45	161	14.7	30.4	130	40.7	T_L
F_H	45	140	14.7	30.4	120	38.3	T_L
F_L	28	124	15.3	31.6	119	32.9	T_L
F_C	28	168	15.3	31.6	135	41.4	T_L
F_H	28	149	15.3	31.6	125	37.7	T_L
F_L	45	128	15.3	31.6	122	34.0	T_L
F_C	45	173	15.3	31.6	138	39.7	T_L
F_H	45	151	15.3	31.6	127	37.7	T_L
F_L	28	124	14.7	30.4	115	35.4	T_H
F_C	28	138	14.7	30.4	120	37.9	T_H
F_H	28	108	14.7	30.4	108	32.9	T_H
F_L	45	124	14.7	30.4	115	35.4	T_H
F_C	45	141	14.7	30.4	121	38.5	T_H
F_H	45	108	14.7	30.4	108	32.9	T_H
F_L	28	132	15.3	31.6	120	34.9	T_H
F_C	28	148	15.3	31.6	123	38.0	T_H
F_H	28	116	15.3	31.6	112	32.7	T_H
F_L	45	132	15.3	31.6	119	35.1	T_H
F_C	45	152	15.3	31.6	127	37.9	T_H
F_H	45	115	15.3	31.6	113	32.3	T_H

(U) Table 12
MA-2 Power Output vs Frequency at Nominal DC and RF Power Inputs

Frequency (MHz)	Power Output (W)		
	T_L	+25°C	T_H
F_C-70	100	119	115
F_C-60	111	134	126
F_C-50	122	142	130
F_C-40	134	148	133
F_C-30	145	154	135
F_C-20	152	155	137
F_C-10	157	156	138
F_C	162	156	138
F_C+10	165	155	135
F_C+20	165	152	130
F_C+30	160	147	125
F_C+40	155	143	125
F_C+50	148	138	113
F_C+60	142	130	106

(U) Table 13
MA-2 Power Output and Efficiency vs Frequency for High and Low Supply Voltages and High and Low RF Inputs

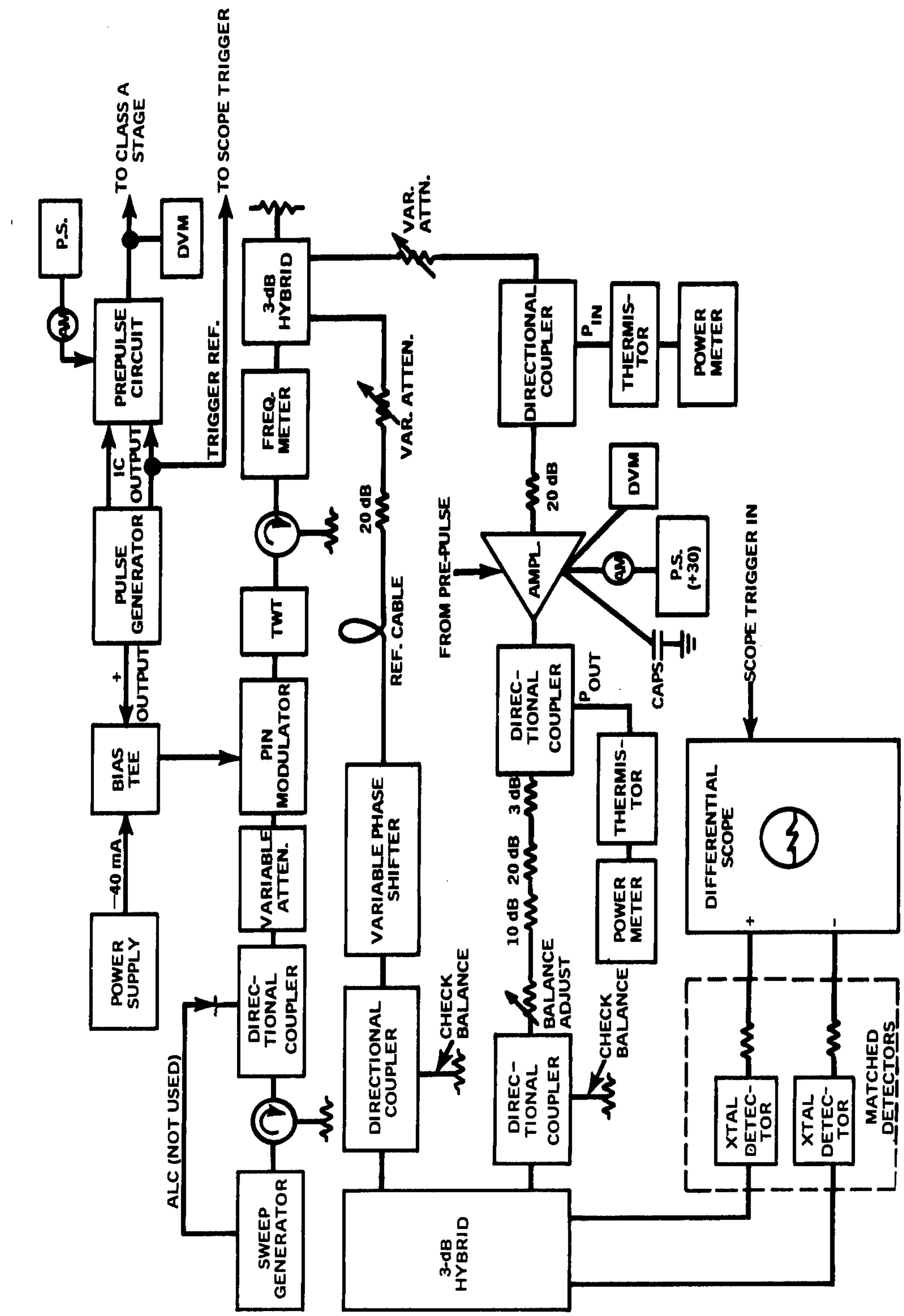
Frequency (MHz)	P_{in} (mW)	P_{out} (W)	V_1 (V DC)	V_2 (V DC)	I_2 (MA)	Efficiency (%)	Temperature (°C)
F_L	28	138	14.7	30.4	133	33.3	+25
F_C	28	164	14.7	30.4	139	38.1	+25
F_H	28	133	14.7	30.4	120	36.5	+25
F_L	45	138	14.7	30.4	134	33.1	+25
F_C	45	164	14.7	30.4	139	37.9	+25
F_H	45	133	14.7	30.4	121	35.3	+25
F_L	28	143	15.3	31.6	136	32.5	+25
F_C	28	174	15.3	31.6	144	37.5	+25
F_H	28	144	15.3	31.6	127	35.0	+25
F_L	45	143	15.3	31.6	136	32.5	+25
F_C	45	173	15.3	31.6	145	37.1	+25
F_H	45	144	15.3	31.6	127	34.9	+25
F_L	28	126	14.7	30.4	123	32.9	T_H
F_C	28	144	14.7	30.4	132	35.0	T_H
F_H	28	109	14.7	30.4	113	30.9	T_H
F_L	45	126	14.7	30.4	123	32.7	T_H
F_C	45	114	14.7	30.4	132	34.8	T_H
F_H	45	109	14.7	30.4	113	29.9	T_H
F_L	28	129	15.3	31.6	130	30.7	T_H
F_C	28	149	15.3	31.6	135	34.1	T_H
F_H	28	117	15.3	31.6	117	30.9	T_H
F_L	45	129	15.3	31.6	130	30.5	T_H
F_C	45	149	15.3	31.6	135	34.0	T_H
F_H	45	117	15.3	31.6	119	30.1	T_H
F_L	28	105	14.7	30.4	126	27.0	T_L
F_C	28	153	14.7	30.4	133	37.9	T_L
F_H	28	122	14.7	30.4	119	32.8	T_L
F_L	45	106	14.7	30.4	132	25.6	T_L
F_C	45	157	14.7	30.4	141	35.8	T_L
F_H	45	137	14.7	30.4	122	35.7	T_L
F_L	28	109	15.3	31.6	136	24.8	T_L
F_C	28	163	15.3	31.6	147	34.3	T_L
F_H	28	142	15.3	31.6	120	36.6	T_L
F_L	45	109	15.3	31.6	138	24.4	T_L
F_C	45	166	15.3	31.6	150	34.2	T_L
F_H	45	149	15.3	31.6	130	35.4	T_L

(U) The listings of power output shown in the tables indicate specification compliance. However, a circulator loss of about 0.5 dB was not introduced in determining the outputs. At the band edges some of the power outputs would be marginal due to circulator losses.

(U) Phase measurements were made at MA using a bridge technique and setup as shown in Fig. 84. In operation, bridge balance is first obtained by using a swept frequency that is fed into the test and reference channels without inserting the module under test. A set of attenuators is measured separately to obtain phase characteristics vs frequency; the insertion loss is set equal to the module gain. Module and attenuator are inserted into the test channel of the bridge, and a section of line is inserted into the reference channel to balance the bridge with the module energized. Using a single frequency results in a null reading being obtained as a reference. Phase shift changes with supply voltage variation are measured by readjusting the bridge to null after changing the supply voltages appropriately and then comparing the new null reading with the reference. The intrapulse linearity is measured by first obtaining a reference reading with the phase bridge nulled, under conditions of constant supply voltage and temperature for the module. The frequency is varied in steps, a reading with the bridge nulled being taken at each frequency. The rate of phase change per 10 MHz is the difference in phase between 10-MHz steps of frequency previously measured. Results of phase measurements on MA-1 and MA-2 are shown in Tables 14 and 15, respectively. Both modules operated within the phase/temperature specification. Neither met the intrapulse phase linearity specifications. The method of measurement, i.e., every 10 MHz, used by MA makes the results questionable. It is felt that two measurement points are insufficient and that measurements 5 MHz or less apart would be more satisfactory. In Table 16 is a listing of results taken under condition of the so-called optimum transmitter collector supply voltage of 29.5 V rather than the nominal 31 V, for MA-2. The slope measurements show a marked improvement over those taken at the nominal supply voltage. However, the results are inconclusive since only one module was tested under this condition. In an array of many modules it would not be practical to adjust power supply voltages individually per module. On the other hand, if it could be shown that most modules performed better with a new supply voltage, then that voltage could be supplied to all modules in an array.

RCA Transmitter

(U) A block diagram of the RCA transmitter is shown in Fig. 85, and a photo in Fig. 86. The preamplifier consists of two stages of amplification to provide an output power of 1.5 to 2.0 W with which to excite the driver stage. The first stage utilizes an HP 35833E transistor biased for Class A operation. The bias is gated such that the transistor draws current only for the duration of the logic transmit pulse. The second stage uses an MSC 3001 transistor operated as a Class C amplifier. The two stages are connected through a very simple and compact interstage network consisting of a length of transmission line with two short shunt stubs, which provides impedance matching from the collector of the first stage to the emitter of the second over the required operating frequency band. A DC return for the emitter of the second stage is provided through a quarter-wavelength, 80-ohm transmission line shorted to ground.



(U) Fig. 84 — Phase bridge

(U) Table 14
Phase Response of MA-1 Power Amplifier

Phase Linearity and Phase Shift		
Frequency (MHz)	Intrapulse Phase Linearity P_{in} = 35 mW, V_2 = 31 V DC	Phase Shift vs Voltage P_{in} = 35 mW, $V_2 \pm 2\%$
F_L	1.43	3.57
F_C	0.49	3.12
F_H	1.26	1.97
Pulse jitter for all conditions is less than 0.5 deg.		
Phase Shift Vs Temperature		
F_C (MHz) from 26°C to 71°C	0.56 degree/°C	
F_C + 80 (MHz) from 71°C to 28°C	0.67 degree/°C	
Intrapulse Phase Linearity vs Frequency		
Frequency (MHz)	$\Delta\phi$ (deg)	$\Delta\phi$/10 MHz (deg)
F_L	1.30	0.48
-50	1.78	1.12
-40	2.90	0.06
-30	2.80	0.18
-20	2.66	1.14
-10	1.52	1.08
F_C	0.48	1.94
+10	2.42	1.24
+20	3.66	0.21
+30	3.45	0.03
+40	3.48	1.32
+50	2.16	1.36
F_H	0.80	

(U) Table 15
Phase Response of MA-2 Power Amplifier

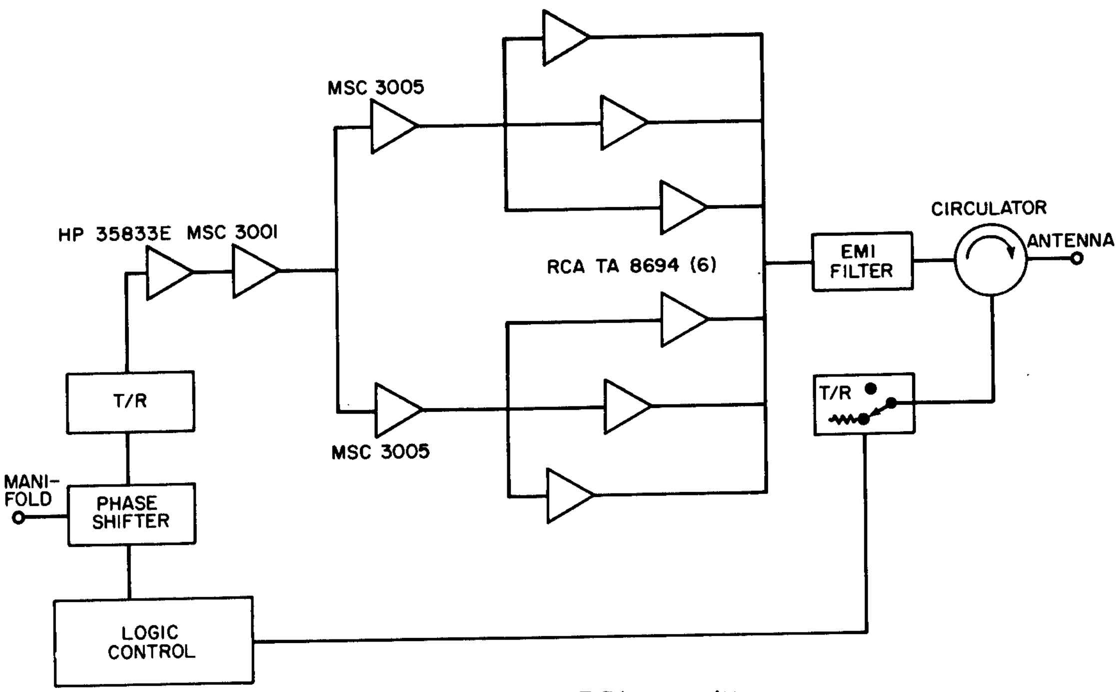
Phase Linearity and Phase Shift		
Frequency (MHz)	Intrapulse Phase Linearity P_{in} = 35 mW, V_2 = 31 V DC	Phase Shift Vs Frequency P_{in} = 35 mW, V_2 ± 2%
F_L	1.96	2.50
F_C	4.05	3.13
F_H	2.76	2.36
Pulse jitter for all conditions is less than 0.5 deg.		
Phase Shift vs Temperature, P_{in} = 35 mW		
F_C (MHz) 26.5°C to 70°C	0.68 deg/°C V_2 = 29.5 V DC	
F_C (MHz) 70°C to 27°C	0.60 deg/°C V_2 = 31.0 V DC	
Intrapulse Phase Linearity vs Frequency P_{in} = 35 mW, V_2 = 31 V DC		
Frequency (MHz)	$\Delta\phi$ (deg)	$\Delta\phi$/10 MHz (deg)
F_L	0.68	4.32
-50	5.00	0.05
-40	5.05	0.25
-30	5.30	0.10
-20	5.40	0.10
-10	5.50	1.15
F_C	4.35	1.06
+10	3.29	1.75
+20	1.54	0.87
+30	0.67	0.23
+40	0.90	1.25
+50	2.15	0.94
F_H	3.09	

(U) Table 16
Phase Response of MA-2 Power Amplifier Vcc = 29.5 V DC

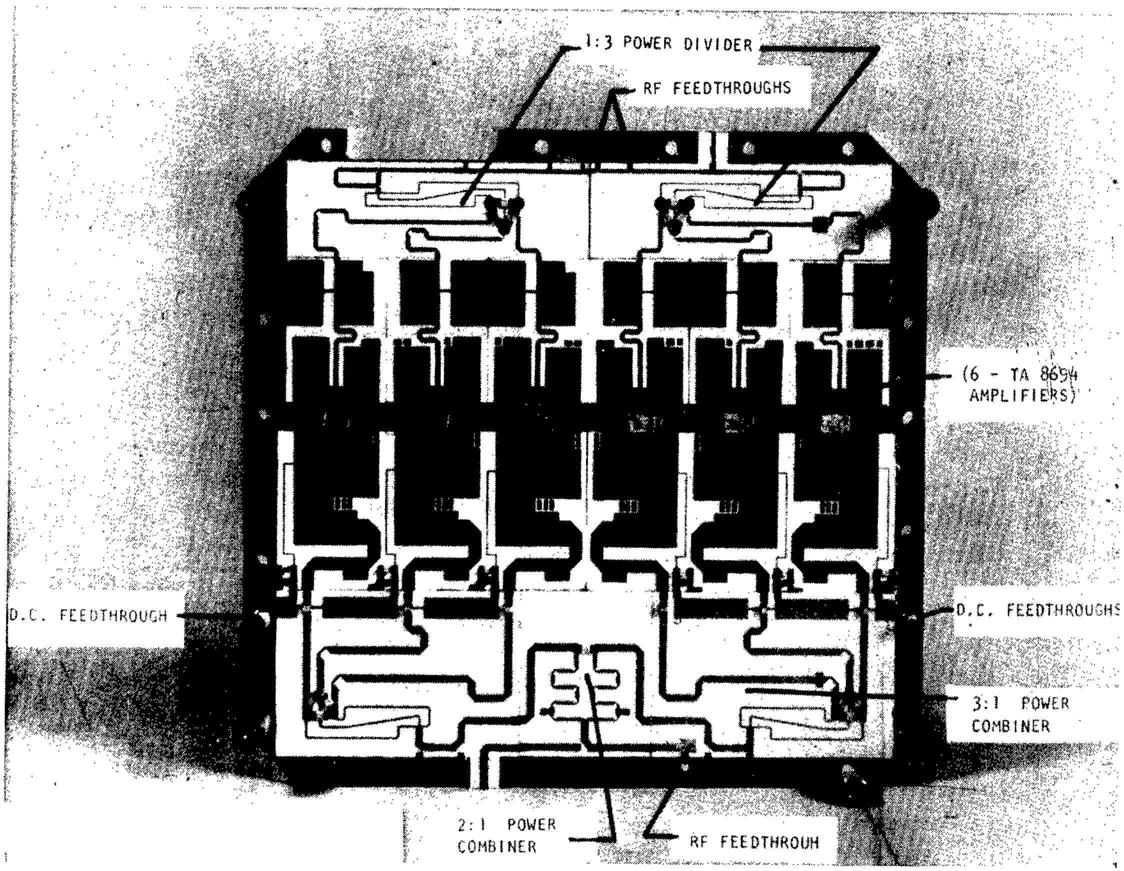
Intrapulse Phase Linearity vs Frequency, P_{in} = 35 mW, V_2 = 29.5 V DC		
Frequency (MHz)	$\Delta\phi$ (deg)	$\Delta\phi$/10 MHz (deg)
F_L	2.06	
-50	2.09	0.03
-40	3.05	0.96
-30	3.72	0.67
-20	3.76	0.04
-10	3.55	0.21
F_C*	2.35	1.20
+10	1.31	1.04
+20	1.05	0.26
+30	1.11	0.06
+40	1.12	0.01
+50	1.13	0.01
F_H	1.72	0.59

*At V_2 = 28.9 V DC, $\Delta\phi$ at F_C MHz was 2.07°

Intrapulse Phase Linearity vs Temperature, P_{in} = 35 mW		
V_2 (VDC)	$T = T_H$ at $\Delta\phi$ (deg)	T = 27°C at $\Delta\phi$ (deg)
29.5	1.50	2.50
31.0	1.80	5.00



(U) Fig. 85 — RCA transmitter



(U) Fig. 86 — RCA transmitter

(U) The gain of the preamplifier is great enough that an attenuator has been inserted prior to it to ensure a low-input VSWR to the transmitter chain.

(U) Temperature stabilization of the bias of the first stage has been accomplished using a thermistor in the base bias circuit and by taking advantage of the collector degeneration provided by a resistor. Collector current variation over the temperature range from -30° to + 10°C is ± 10%.

(U) The driver stage uses two MSC 3005 transistors in parallel, each of which drives three final amplifier transistors in parallel, each of which is biased for Class C operation. Both stages together require a nominal input power of 1.5 W and provide a total power output of 18 W with which to drive the high power amplifier (HPA). A low-resistance DC return for the emitter is provided by the inductance of the resonant circuit. The two individual amplifiers are excited by using a Wilkinson 1:2 power divider. An additional quarter-wavelength of line is inserted between the power divider and one of the amplifiers such that reflections from the two amplifiers are dissipated in the isolation resistor of the power divider and the reflection coefficient seen at the input to the power divider is very low. Hence the second stage of the preamplifier sees a fairly good 50-ohm

load and is not detuned. A similar quarter-wavelength line is inserted in the output of the other driver amplifier so that ultimately the signal from each driver amplifier is in phase at the input to the final amplifiers. This stage was designed with sufficient gain to allow a 1-dB attenuator to be inserted in each driver amplifier output to provide some detuning protection. In the event of TA 8694 failure, the attenuators provide an additional 2 dB of isolation from the mismatch caused by the failure and hence additional protection against the failure of one of the MSC 3005s.

(U) The HPA consists of six TA 8694 transistor amplifiers connected in parallel in two groups of three amplifiers, each excited through a 1:3 Wilkinson power divider. An extra line length of 60 degrees and 130 degrees, respectively, is added to each of two lines from the power divider to the amplifiers. This dissipates most of the power reflected from the final amplifiers to the isolation resistors of the power divider. Phase coherence at the input to the 3:1 Wilkinson power combiner after the amplifier is obtained by inserting an extra 60 degrees and 120 degrees in the proper output transmission lines. The two halves are then combined using a 2:1 Wilkinson combiner.

(U) As with the other high-level amplifiers, these are operated with Class C bias. The nominal power required to drive the HPA is 15.5 W, and it yields an output power of 140 W or greater at room temperature.

(U) The major mechanical parts of the module assembly are the carrier plates to which substrates are soldered, a spacer between carriers, and an enclosure. The two carrier plates are first attached to the spacer which serves to separate them. This assembly is then mounted in the case by means of machine screws.

(U) The carrier plates were fabricated from 0.008-in.-thick molybdenum sheet. Molybdenum was chosen because its coefficient of thermal expansion is close to that of the substrate material. The molybdenum carriers were plated, and, after plating, the substrates were soldered to the carriers.

(U) The spacer was used to separate the two carrier plates and to provide a structure for mounting the circulator. The spacer was fabricated from aluminum.

(U) The enclosure was fabricated from Lockalloy (62% Be, 38% Al) to minimize weight. The weight of Lockalloy is 0.075 lb/in.^{3} It has a Young's Modulus of 28×10^6. The ratio of modulus to density is an important structural parameter. The modulus-to-density ratio for Lockalloy is three to four times that of aluminum.

(U) All circuitry is of thin- or thick-film hybrid construction. The microwave circuits were etched on alumina substrates which were then soldered to the 0.008-in.-thick molybdenum carriers to provide reliable RF and thermal paths. The two molybdenum carriers were bolted to an aluminum rib spacer, giving a structure with the necessary rigidity. The transistors are equipped with low-thermal-resistance flanges which have been soldered to the carriers. The thickness of each of the alumina substrates was selected to optimize the performance of each of the circuits.

(U) All electrical connections on the substrates were welded rather than soldered, to achieve maximum reliability. Hybrid mounted components such as chip capacitors and resistors were equipped with welded-on ribbon leads which were subsequently welded to the circuit metalization. In addition to high reliability, this process ensured reproducibility and offered maximum potential for automation and cost-effective production. Chip-type diodes were used in the T/R switches, limiter, and phase shifter, and chip-type complementary symmetry, metal oxide semiconductor (COS/MOS) devices were used in the phase shifter logic-driver circuitry in the two prototype modules delivered. Future modules will employ beam-lead diodes and sandwich structure beam-leaded COS/MOS devices.

(U) The complete module can be hermetically sealed to withstand the low-pressure environment without incurring either multipactor or ionization breakdown. The two prototype modules, however, were left unsealed for convenience in evaluation.

(U) Fabrication of the RF components begins with the thin-film circuitry. The etched thin-film gold pattern forms all the passive elements of the circuitry, including transmission lines and impedance-matching circuitry. To this matrix are added the elements making up the finished circuit: active devices (diodes, transistors, integrated circuits) and passive devices (capacitors, resistors, interconnections).

(U) The order of assembly is as follows: To each etched substrate is added the full complement of devices needed to complete that circuit; then the individual completed circuits are soldered to a metal carrier plate. There are two such plates in the module, assembled back-to-back, forming a "sandwich" which is installed in the enclosure as a unit.

(U) The active devices are of three types: (a) packaged transistors, (b) unpackaged chip diodes, and (c) beam-lead integrated circuits, transistors, and diodes. The packaged transistors are flange-mounted, installed using machine screws after circuit assembly and soldering. The chip diodes are eutectic-die mounted into the circuit with a semiautomatic die mounting machine. The final connection to the circuit is made by thermocompression wire bonding, using 0 001-in.-diameter gold wire. The beam-lead devices are installed using a thermocompression beam-lead bonding machine. This machine is also semiautomatic, thus allowing high speed assembly of these devices.

(U) The passive elements bonded into the circuit are chip resistors, chip capacitors, interconnections, and crossovers. The capacitors and resistors are purchased items. They are inspected upon delivery and then gold ribbon leads are attached to them, using parallel-gap welding techniques. Parallel-gap welding is a technique which employs a pulse of high current between two electrodes as a source of heat while the electrodes are impressed at a specific pressure upon the material to be welded. This method of lead attachment is superior to any available leads, as well as being directly compatible with the later assembly processes.

(U) These devices with leads attached are then parallel-gap welded into the final circuit. This process is used because it produces a strong and reliable weld between gold ribbon and electroplated thin-film gold. There are no intermetallic alloys or oxides to weaken the interface. The crossovers and interconnections are formed from gold ribbon and are welded into the circuit. These have been tested under stress and are very reliable. Since

the crossovers are of formed ribbon, the insulator is air, thus minimizing RF cross-coupling due to mutual capacitance.

(U) The assembled circuits are next soldered onto the molybdenum carrier plate. The carrier plate is gold plated for maximum solderability. A good thermal match between substrate and plate is achieved, since alumina and molybdenum have very similar coeff-cients of expansion. The finished carrier plate with circuits attached is then mated back-to-back with its complementary assembly. The RF and DC feedthroughs are then installed, and the unit is ready for emplacement in the enclosure. This is accomplished with machine screws and lock washers. And last, the RF and logic connectors are welded in place. The module assembly is then complete, with the exception of the enclosure lids which are designed to be hermetically sealed by using electron beam welding.

(U) An electromagnetic interference (EMI) filter is required to reduce power amplifier harmonics to the specified level below the fundamental. Table 17 shows the budget selected to achieve this requirement.

(U) Table 17
Budget for Harmonic Rejection

Component	Harmonic Below Fundamental		
	Second Harmonic (dB)	Third Harmonic (dB)	Higher Harmonics (dB)
Power amplifier	> 20	> 25	> 25
Circulator	> 25	> 8	—
EMI filter	> 5	> 17	> 25
Total	> 50	> 50	> 50

(U) The EMI filter incorporated in the module is a two-section, low-pass filter. It is configured on a 0.050-in. alumina substrate using distributed L and C microstrip sections. It has an insertion loss of 0.2 dB in the passband with greater than 7-dB second-harmonic rejection and greater than 20-dB third-harmonic rejection.

(U) Each of the components met the harmonic-rejection budget in Table 17. However, when combined, the module's second-harmonic output did not meet specification. The reason for this is not presently understood. It is felt that a box resonance or feedback could account for this result.

(U) The RCA tests on the transmitter portions of the modules were made using bench setups incorporating standard commercial test equipment and average reading power meters for reading amplitude; a phase bridge was set up for phase measurements. Results are given in Tables 18-21. Test setup corrections to power and gain readings are listed in Table 22. Since the corrections listings are not at precisely the same frequencies, their use leaves some margin for error because interpolation is not linear. In any case, the corrections appear to involve less than 10 W at any frequency close to the test frequencies.

(S) Table 18
RCA-1 Transmitter Performance with Varied Power Supply or RF Input, at 250°C

Frequency (MHz)	P_{in} (mW)	V_{cc} (V DC)	P_{out} (W)	I_{cc} (mA)	Efficiency (%)	Gain (dB)	Phase Settling (deg)	Rise Time (nsec)	Amplitude Droop (%)	Input VSWR	Spurious Oscillations (dB)	Harmonics 2nd (dB)	Harmonics 3rd (dB)	Harmonics 4th (dB)
1187	80	29.4	120	140	29.2	31.7								
1187	80	30.0	122	144	28.2	31.8	7.4	25	1.0	1.43	>60	45	>65	>65
1187	80	30.6	125	148	27.6	31.9								
1250	80	29.4	101	121	28.4	31.0								
1250	80	30.0	106	126	28.0	31.2	5.3	25	<.5	1.58	>55	47	>60	>60
1250	80	30.6	110	130	27.6	31.4								
1313	80	29.4	112	110	34.6	31.4								
1313	80	30.0	117	114	34.2	31.6	5.1	30	<.5	1.58	50	35	>60	>60
1313	80	30.6	122	120	33.2	31.8								
1187	63	30.0	122	144	28.2	32.8								
1187	80	30.0	122	144	28.2	31.8								
1187	101	30.0	122	144	28.2	30.8								
1250	63	30.0	103	121	28.4	32.1								
1250	80	30.0	104	124	28.0	31.1								
1250	101	30.0	106	127	27.8	30.2								
1313	63	30.0	113	110	34.2	32.5								
1313	80	30.0	116	114	33.9	31.6								
1313	101	30.0	117	117	33.3	30.7								

Note: Blanks imply no change.

(S) Table 19
RCA-2 Transmitter Performance with Varied Power Supply or RF Input, at 25°C

Frequency (MHz)	P_{in} (mW)	V_{cc} (V DC)	P_{out} (W)	I_{cc} (mA)	Efficiency (%)	Gain (dB)	Phase Settling (deg)	Rise Time (nsec)	Amplitude Droop (%)	Input VSWR (dB)	Spurious Oscillations (dB)	Harmonics 2nd (dB)	Harmonics 3rd (dB)	Harmonics 4th (dB)
1187	80	27.4	121	146	28.2	31.8								
1187	80	30.0	123	148	27.7	31.8	60	30	<.5	1.50	>50	35	>50	>50
1187	80	30.6	125	153	26.7	31.9								
1250	80	29.4	112	128	29.8	31.5								
1250	80	30.0	115.5	134	28.7	31.6	5.1	30	<.5	1.38	>50	38	>50	>50
1250	80	30.6	119.5	140	27.9	31.7								
1313	80	29.4	101.5	127	27.2	31.0								
1313	80	30.0	103.0	132	26.0	31.1	10.0	30	<.5	1.50	>50	40	>50	>50
1313	80	30.6	106.0	136	25.5	31.2								
1187	63	30.0	124	150	27.6	31.9								
1187	80	30.0	123	150	27.3	31.9								
1187	109	30.0	123	150	27.3	30.9								
1250	63	30.0	116.5	134	29.0	31.7								
1250	80	30.0	116.0	135	28.6	31.6								
1250	101	30.0	116.0	136	28.4	30.6								
1313	63	30.0	103	130	26.4	32.1								
1313	80	30.0	103	132	26.0	31.1								
1313	101	30.0	103	132	26.0	30.1								

Note: Blanks imply no change.

(S) Table 20
RCA-2 Transmitter Performance with Temperature or High VSWR Load, with Input Power of 80 mW and V_{cc} of 30 V DC

Normal Load, Temperature Varied								
Frequency (MHz)	Temperature (°C)	P_{out} (W)	I_{cc} (mA)	Efficiency (%)	Gain (dB)	Phase Settling (deg)	Rise Time (nsec)	Amplitude Droop (%)
1187	-30	128	154	27.7	32.0	5.7	40	<.5
1250	-30	125	136	30.6	31.9	7.8	50	<.5
1313	-30	107	134	26.6	31.3	10.5	30	<.5
1187	+70	118.5	143	27.6	31.7	6.7	40	1.2
1250	+70	115.0	130	29.5	31.6	7.5	35	1.0
1313	+70	101.5	124	27.3	31.0	11.3	35	<.5

Constant Temperature, Variable Load							
Frequency (MHz)	Temperature (°C)	Load VSWR	Operating Time (sec)	P_{out} Before Test (W)	P_{out} After Test (W)	I_{cc} Before Test (mA)	I_{cc} After Test (mA)
1187	25	5:1	30	123	123	148	148
1250	25	5:1	30	115.5	115.5	134	134
1313	25	5:1	30	103	103	132	132

(S) Table 21
RCA-1 Transmitter Performance with Temperature of High VSWR Load
Normal Load, Temperature Varied

Frequency (MHz)	P_{in} (mW)	V_{cc} (V DC)	Temperature (°C)	P_{out} (W)	I_{cc} (mA)	Efficiency (%)	Gain (dB)	Phase Settling (deg)	Rise Time (nsec)	Amplitude Droop (%)
1187	80	30	-30	128	151	28.2	32.0	5.7	30	<.5
1250	80	30	-30	110	114	32.2	31.4	3.8	30	<.5
1313	80	30	-30	117	108	36.1	31.6	4.0	40	<.5
1187	80	30	+70	116	135	28.6	31.6	8.1	30	1.1
1250	80	30	+70	103	119	28.8	31.1	6.3	25	1.0
1313	80	30	+70	106	108	32.7	31.2	7.1	30	<.5

Constant Temperature, Variable Load

Frequency (MHz)	P_{in} (mW)	V_{cc} (V DC)	Temperature (°C)	Load VSWR	Operating Time (sec)	P_{out} Before Test (W)	P_{out} After Test (W)	I_{cc} Before Test (mA)	I_{cc} After Test (mA)
1187	80	30	25	5:1	30	124	124	147	147
1250	80	30	25	5:1	30	106	106	129	129
1313	80	30	25	5:1	30	119	119	116	116

(S) Table 22
Corrections for Power and Gain

	RCA-1		RCA-2	
Frequency (MHz)	Point (W)	Gain (dB)	Point (W)	Gain (dB)
1186	121.2	31.80	124.9	31.93
1190	120	31.76	124	31.90
1194	119	31.72	125	31.94
1198	118	31.69	123.4	31.88
1202	117.5	31.67	123.4	31.88
1206	115.5	31.59	122.7	31.86
1210	116	31.61	123.4	31.88
1214	115.3	31.57	122.7	31.86
1218	118	31.69	125.2	31.95
1222	116	31.61	122.1	31.84
1226	116	31.61	120.5	31.78
1230	116	31.61	121.6	31.82
1234	114.5	31.56	120.5	31.78
1238	113.5	31.52	119.0	31.72
1242	111	31.42	116.9	31.65
1246	110.5	31.40	118.4	31.70
1250	108	31.30	117.1	31.65
1254	108.5	31.32	118.3	31.70
1258	107.6	31.29	119.5	31.74
1262	101.6	31.29	119.2	31.73
1266	111.3	31.43	120.7	31.79
1270	115.2	31.58	120.8	31.79
1274	117	31.65	119.9	31.76
1278	117	31.65	116.5	31.63
1282	120.5	31.78	117.8	31.68
1286	118.5	31.71	115.6	31.60
1290	120.5	31.78	116.0	31.61
1294	123	31.87	115.3	31.59
1298	121	31.80	113.1	31.50
1302	120	31.76	112.3	31.47
1306	120	31.76	110.0	31.38
1310	122	31.83	106.3	31.23
1314	124	31.90	102.9	31.09

(S) Power output over the specified band meets requirements although it is at times marginal, if one considers possible errors due to the microwave measuring setup. Gains over the band are adequate also. Phase settling was somewhat higher than the specification value of 5 degrees, but rise time was well within the required 50 nsec. Pulse amplitude droop was within the required 5%. Efficiencies of both module transmitters were below the required 40% and were due, it is felt, to the need for six paralleled power transistors instead of the four that the other contractors used. However, RCA felt that their improved output transistor to be used in the final models would yield considerable improvement to this value. Harmonic content other than second was within specification. The contractor is investigating this design discrepancy.

(U) Table 23 lists phase variation with temperature at constant frequency and supply voltage, and indicates that for a 100°C change in temperature, less than 15 degrees of phase change occurs.

(S) Table 23
Transmitter Phase Shift With Temperature

Frequency (MHz)	P_{in} (mW)	V_{cc} (V DC)	Temperature (°C)	Phase (deg)
MA-1 Transmitter				
1250	80	30	-30	0
			+25	10.8
			+70	14.6
MA-2 Transmitter				
1250	80	30	-30	151.8
			25	160.8
			+70	165.1

Westinghouse Transmitter

(U) A block diagram of the Westinghouse transmitter is shown in Fig. 87; a photo of the unit is shown in Fig. 88. There are five stages of amplification with an overall gain of 34 dB. The first two stages utilize Hewlett Packard transistors operating Class A. The next stage uses two paralleled Microwave Semiconductor Corporation transistors mounted on a Westinghouse chip carrier and operating Class C. The last two stages are Power Hybrids, Inc. (PHI) devices, also operating Class C. This block diagram is significantly changed from the originally proposed approach, which used MSC devices for all the Class C stages and had paralleled transistors in only the output stage. Although the block diagram for the amplifier was changed, the basic design philosophies remained intact. Specifically, the first of these was the implementation of the three Class C stages using chip-carrier-mounted transistors. These were used to enhance the bandwidth capabilities of the transistors and to simplify the matching circuits which were used.

(U) The second major design approach which was carried through the program was the utilization of 90° hybrid quadrature couplers between all Class C stages. This concept,

a product of past experience, provided each transistor with isolation from any succeeding stage. This property is especially desirable during turn-on when the transistors' impedances are going through wide variations.

(U) Another change which was made during the program was the selection of PHI devices in the last two stages. This choice was made during the program and was based on the results of an evaluation of both the MSC and PHI devices. Basically, it was concluded that the MSC 80135 was capable of the necessary output power, but that its package input and output impedances would not afford a 10%, 1-dB bandwidth. Therefore an attempt to build an internally matched chip carrier for this chip and for the MSC drivers was undertaken. Parallel to this was an effort to evaluate the new PHI devices which were recently introduced. The PHI devices were eventually chosen for the last two stages for reasons which will be discussed later. In addition, the Class C predriver was chosen to be the MSC 2003 chip, mounted on a Westinghouse chip carrier.

(U) Thus, the final amplifier was configured to have four PH 8041s in the output stage with the intention of developing greater than 140 W at center band. These in turn are driven by two PH 8040s which deliver about 12-15 W each, with the two MSC 2003s in the Class C predriver producing 2-3 W each.

(U) In the low-level Class A predriver, two series HP-11s are used to amplify the input power up to the 600-800 mW level. A change was made from a parallel configuration to the series approach when the evaluation of a single HP-11 indicated that it had enough bandwidth and output power to drive the first Class C stages. The series approach also allowed for more gain in the amplifier and, therefore, more isolation from the phase shifter could be obtained by virtue of a higher attenuator setting in the gain trimmer preceding the amplifier.

Westinghouse Chip Carrier Design

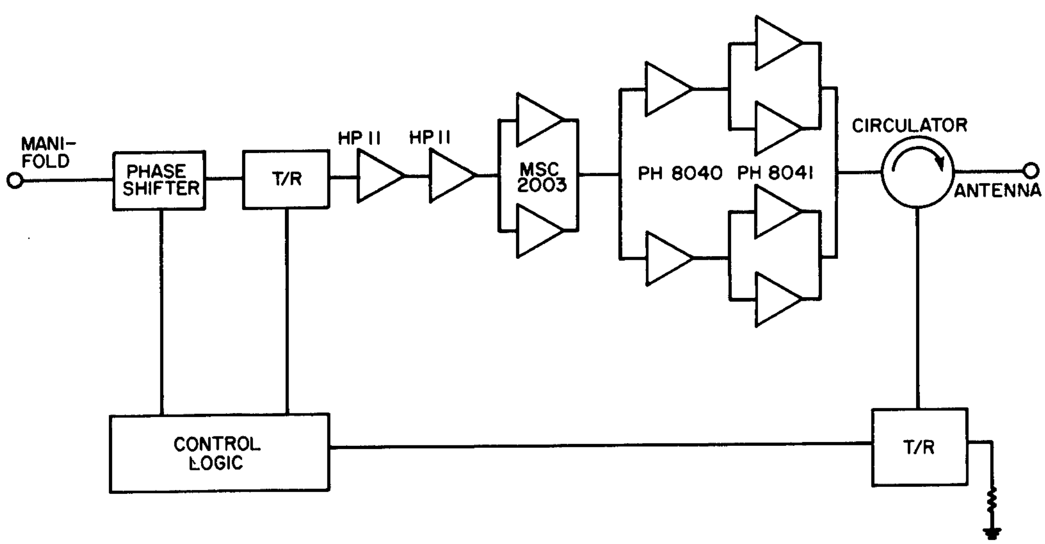
(U) One of the primary tasks at the beginning of this program was to develop a chip carrier for use with the MSC 80135 chip transistor. This transistor had the required peak power output, but it was available only in an unmatched package, which Westinghouse felt would limit the bandwidth. Westinghouse, therefore, chose to develop a chip carrier which would enhance the inherent bandwidth capability of the chip.

(U) This effort had two primary goals. The first goal was to take the 0.5-ohm input impedance of the device and match it to 10 ohms by means of input shunt-capacitor tuning. The second was to shorten the output lead lengths to minimum to cut down on circulating currents and therefore improve both output power and efficiency.

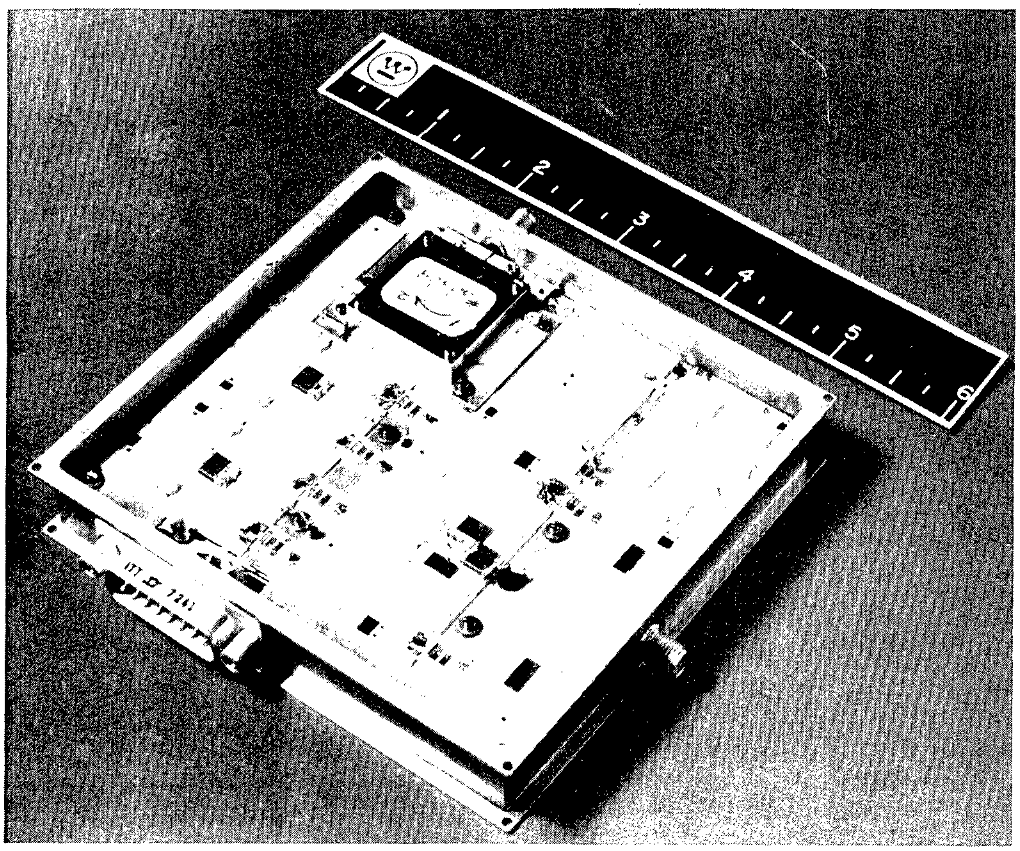
(U) The first step in accomplishing this task was to characterize the device on an intermediate chip carrier which would be very similar to the final one. The intermediate carrier was not tunable and afforded only a mounting pad for RF testing. This carrier had, as did the final carrier, one feature which was considered essential to operation of the transistor chip and which was lacking to some degree in both the PHI and MSC packages. The feature was a uniform grounding technique which assured fulfillment of

two important electrical considerations. First, the ground strips to which the base bond wires are attached are directly connected to the circuit ground plane as close as possible to the transistor chip. This assures the least base lead inductance possible. Second, the base strips are continuously connected to the ground plane along the longitudinal length of the chip, resulting in the same exact physical path length from each chip case side to ground. This is intended to provide even power splitting as a result of even base lead inductance to the various cells.

(U) At the completion of the characterizations the final carrier input matching was designed. The method of approach used a hybrid technique to construct a synthetic quarter-wave line section in series with each pair of transistor cells and then combined six of these sections in parallel at the input lead to yield a net input impedance greater than 10 ohms. The quarter-wave sections themselves were made with selected lengths of bond wire in series with the transistor cells, and shunt capacitors to ground are also attached to these wires.



(U) Fig. 87 — Westinghouse transmitter

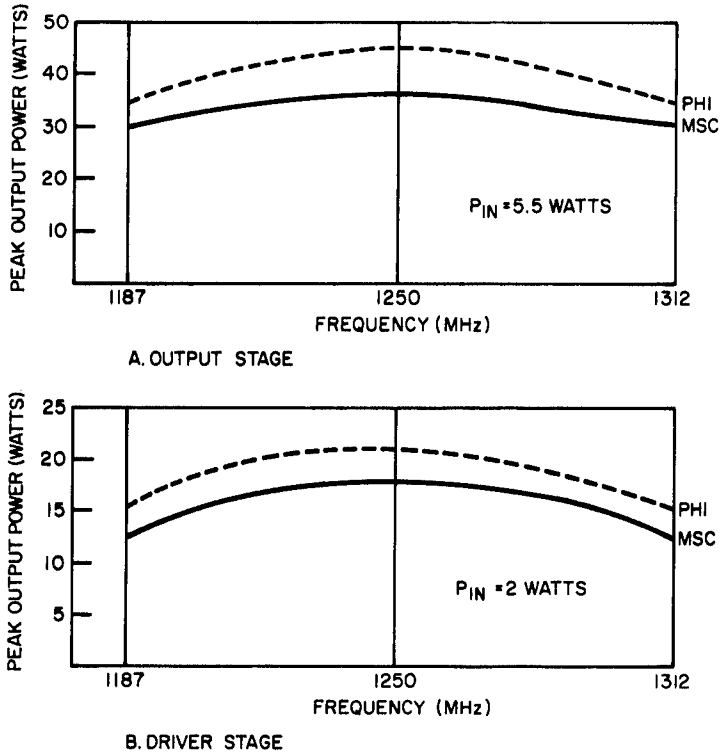


(U) Fig. 88 — Westinghouse transmitter

Comparison of MSC and PHI Devices

(U) Early in the program, the decision was made to include the recently introduced PHI devices in the power amplifier evaluation. The output stage candidate was the PH 1520, which was a chip-carrier-mounted device with both input and output tuning. Initial tests of this device indicated that it had sufficient power output and bandwidth, but exhibited a tendency to "snap on" as the input power level increased. This led to elimination of the output tuning on the carrier which was suspected of causing this abrupt turn-on characteristic. A minor change in the package was also made to facilitate mounting. The modified device was assigned the designation PH 8041; the driver stage with similar modifications is the PH 8040.

(U) The performance of these devices was compared with the MSC 80135 and MSC 2010 chip on Westinghouse carriers. Figure 89 shows a comparison of the output power performance of these devices. The PHI output stage had collector efficiences typically in the 50-55% range, while the MSC device showed 52 to 55% efficiencies. The PHI device appeared to be more rugged, as indicated by its ability to withstand short-circuited outputs with no apparent damage.



(S) Fig. 89 — Performance of PHI and MSC devices

(U) In the final assessment of the transistor comparisons it was decided to use the PHI drivers and outputs. This decision was weighted with a primary concern for output power after combiner and circulator losses and the demonstrated superior ruggedness of the PHI devices. Also weighting the decision was the time yet required to assure that the Westinghouse chip carrier designs would be reproducible. In addition the efficiency data that had been taken to that point indicated that even the lower PHI figures would be sufficient to meet specifications of the module.

(U) Many of the initial tests and evaluations of the PHI transistors for this program were conducted on the basic amplifier blocks of one PH 8040 driving two PH 8041s. Results seen at this stage of the development indicated both wide bandwidth, extremely high power (110 W per two output devices), and overall efficiency greater than 45%. Subsequent loss of both output power and efficiency were attributed mainly to two causes. First was the loss of power and bandwidth when the power amplifier subsystems were put into the modules. Second, the loss of output power through resistive losses in both the 90° quadrature hybrid couplers in the output of the power amplifier and in the printed collector chokes, especially in the output stages, was in excess of the predicted loss for these items. Data on the hybrid coupler used in the outputs indicated loss for two stages of couplers approaching 1 dB. This figure exceeded expected losses in these couplers from past utilization by 0.15 to 0.25 dB per coupler. Also adding to the overall efficiency problem was the fact that the output chokes which were thick-film printed

instead of straight wire chokes exhibited DC resistances of 0.5 ohm typically and therefore caused drops of between 1 and 2 V during a current pulse for the output transistors.

Test Results

(U) Table 24 lists results of module tests conducted at Westinghouse. The two delivered modules exhibited power outputs of between 105 and 140 W across the band with transmitter efficiencies of 18% at low frequency to 35% at the upper frequency. Amplifier subsystems tests, which were conducted before the subsystems were assembled in the module, indicated power output of 20 to 30 W in excess of this with correspondingly higher efficiencies.

(U) In addition to the output peak power and efficiency specifications, the power amplifiers were thought to be marginal in other areas. Due to odd power-amplifier behavior in the modules, performance in the areas of intrapulse phase linearity and phase settling was especially in question. As seen in the tabulation of transmitter data, intrapulse phase deviation particularly is in the order of 10:1 out of specification. During the temperature testing of the modules the amplifier performances dropped off at both high and low temperature, indicating two problems. First, at low temperature the biasing on the Class A predrivers did not compensate for the drop at low temperatures in the DC gain of the devices. Second, as shown in the high-temperature tests the Class C stages appeared to exhibit the effects of high junction temperature with a concomitant falling off of output power. Results of these tests are shown in Figs. 90 and 91.

(U) From the results of this part of the module program it was evident that a number of improvements could be made in the transmitter. A few areas of concern are: the problems which arose when the amplifier was mounted into the module; effects such as narrower bandwidth in the module than on a subsystem level, which were traced to the designs of both the Class A and Class C predrivers; unexpectedly high loss of output power and corresponding loss of efficiency, which were traced to load circuits not being designed to match to optimum collector load-impedance values.

(U) An improved thermal design will allow the transistors to run at lower junction temperatures in future modules. This will also have an effect on output power in that phase response from transistor to transistor will be more uniform and combining losses will be reduced.

NRL Transmitter Measurements

(U) Test equipment for evaluating the transmitter portions of modules was the newly received Scientific-Atlanta (S/A) Pulsed Microwave Measurement System shown in Fig. 5. The two racks comprising the S/A equipment are located at the left in the photo. When originally installed in the NRL test facility, the equipment was found to be inoperative due to design errors. A considerable time lapse occurred during which redesign took place. In the meantime those modules which were delivered by the contractors underwent preliminary receiver testing on the HP Automatic Network Analyzer (which

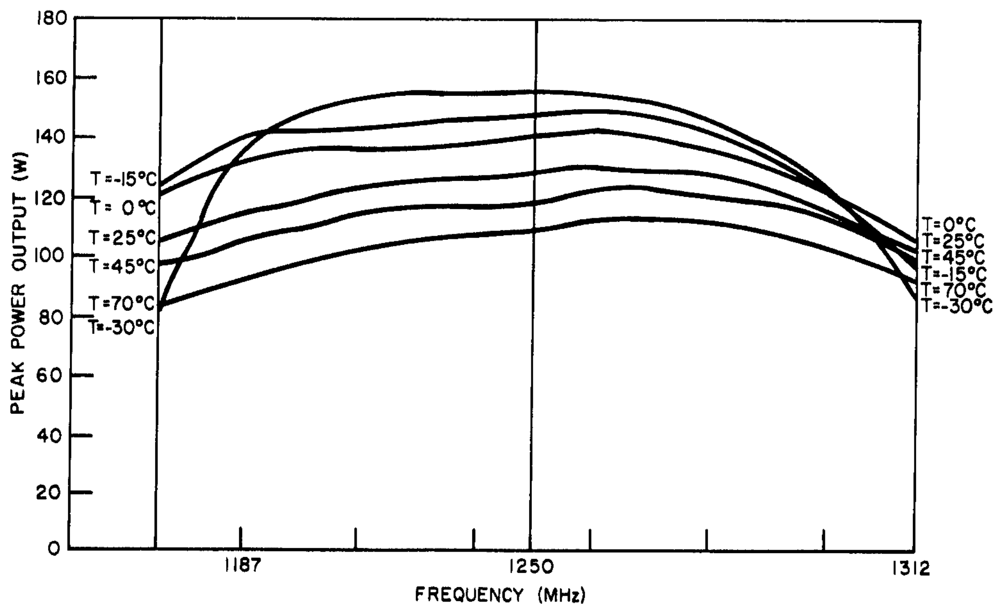
was also new and which had its own "shakedown" problems). The HP problems were subsequently resolved and receiver testing was to begin at NRL when it was discovered that some of the modules had failed, apparently from corrosion due to high sulfur content in the air. The NRL test facility was located adjacent to a sewage processing plant. A decision was made to move the test facility to a building further away from the offending plant, and the decision was soon carried out. Failed modules were sent back to contractors for receiver repair, and the test equipment was temporarily installed in a laboratory until final quarters for it became available. Receiver tests were run as modules became available. When it appeared that the S/A gear was usable, an attempt was made to make module transmitter measurements. It was then discovered that several modules contained failed transmitters. In the case of the RCA modules, the digital portions had failed after preliminary testing and no significant transmitter data were taken. It was found that all transmitters did operate at some time and, when operative, did produce at least 100 W output at the center frequency.

(U) Due to the design of the S/A Measurement System it was necessary to test the transmitters in a "burst" mode rather than at a constant repetition rate and a 1% duty factor. To accomodate the S/A requirements, it was necessary to subject the transmitters to bursts of RF power at a 33% duty factor, with the repetition rate of bursts maintained at 3 kHz to satisfy the 1% duty factor requirement of the transmitters. This necessitated the design and construction of a pulse generator by NRL in order to synchronize the test equipment properly at 3 kHz.

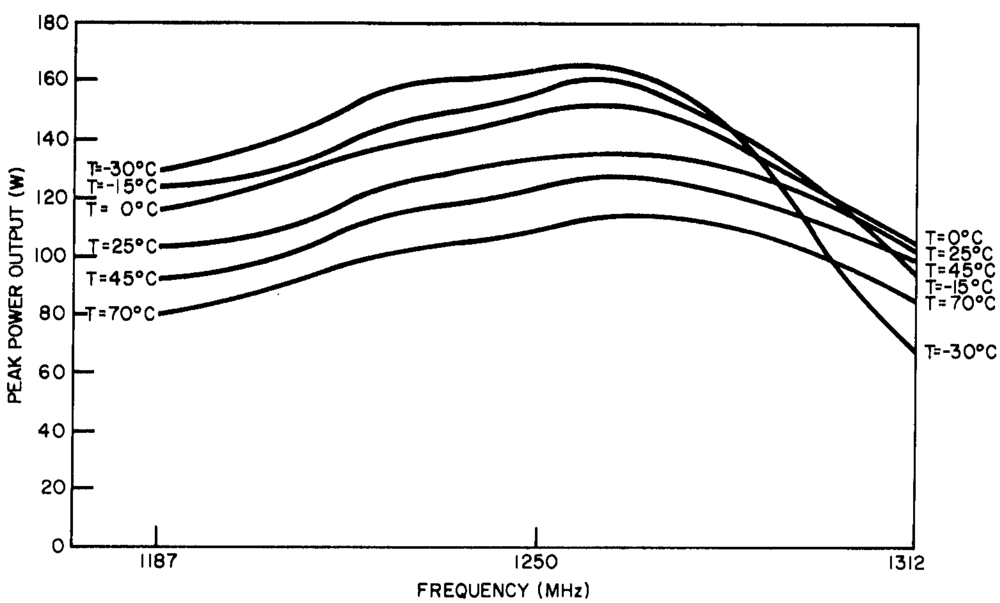
(S) Although the S/A Measurement System was designed to operate under computer control, when initially installed, manual testing methods were employed. All RF power adjustments to the units under test, phase state changes to the modules, and power supply voltage changes (for the modules) were made manually. This caused considerable loss of time during testing and further time loss when recalibration of the test equipment was performed, since the module first had to be removed from the setup. Data recording was also done manually. Frequency changes to the S/A system were made by a digital dial control and pushbutton arrangement which required the operator to first set the frequency digits on the dial. When the pushbutton was pressed, information in digital form was transferred from the dial. This caused generation of an analog error signal which caused the frequency change. The need for all these manual operations and the ensuing time per measurement precluded the use of 41 frequencies as was done during receiver testing. Instead, testing was done at five frequencies, center F_C, the specified band edges F_L,F_H, and an overall band F_{LL},F_{HH}. The frequencies are F_{LL} = 1150 MHz; F_H = 1310 MHz; F_L = 1190 MHz; F_{HH} = 1350 MHz; F_C = 1250 MHz. When frequency is changed, an amplitude-leveling loop within the S/A system maintains the RF signal level constant at the output of the RF signal source. However, the level at the module under test varies with frequency due to the microwave components that follow the signal source output. For each frequency, therefore, a level adjustment must be made by means of a variable attenuator.

(S) Table 24
Westinghouse Transmitter Measurements

Parameter	W-1	W-2
Power output	104 W (min)	105 W (min)
RFI	- 30 dB	- 30 dB
Transmit efficiency	32% (max) 18% (min)	36% (max) 19% (min)
Transmit gain	30 dB (min)	30 dB (min)
Spurious intrapulse noise	- 50 dB	- 50 dB
Spurious oscillation	- 50 dB	- 50 dB
RF amplitude droop	3.5% at F_c	3.9% at F_c
Phase sensitivity to DC	0.25 degrees/Volt	0.19 degrees/Volt
Harmonic on transmit	- 48 dB (min)	- 48 dB (min)
Phase settling	±17 degrees	±5 degrees
Amplifier rise time	20 nsec	22 nsec
Phase sensitivity to Temperature	0.125 degrees/C_{max}	0.25 degrees/C_{max}
Phase sensitivity to input power	±3.5 degrees/± 1 dB	±4 degrees/± 1 dB
Insertion phase length	7200 degrees	7200 degrees
Intrapulse phase linearity	11 degrees peak	9 degrees peak
Intrapulse amplitude linearity	0.5 dB	0.7 dB
Pulse-to-pulse phase deviation	0.3 degrees	0.5 degrees
Pulse-to-pulse amplitude deviation	0.24 dB	0.23 dB
Phase tracking between modules	17 degrees peak	
Amplitude tracking between modules	0.4 dB peak	

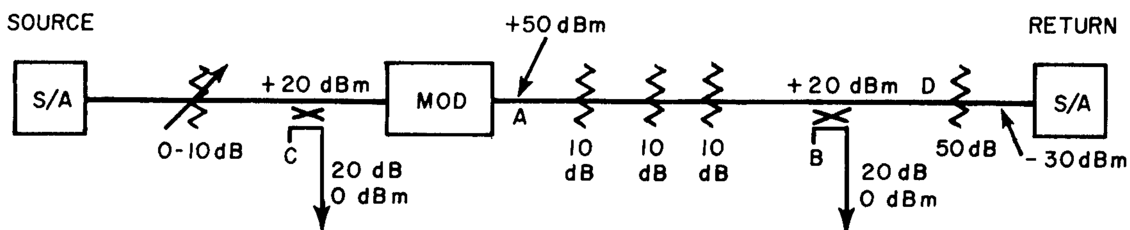


(S) Fig. 90 — Results of transmitter W-1 temperature tests; P_{in} = 0.1 W, pulse width 100 μsec, duty cycle 1%



(S) Fig. 91 — Results of transmitter W-2 temperature tests; P_{in} = 0.1 W, pulse width 100 μsec, duty cycle 1%

(U) Due to the extenuating circumstances just described, the NRL measurements were restricted to phase and amplitude measurements at five frequencies, three RF power input levels (100 mW ± 1 dB) and three sets of power supply voltage levels (nominal ± 2%). The actual test setup is shown in Fig. 92 with details regarding directional couplers and attenuators as used. These items were separately calibrated on the HP Automatic Network Analyzer at the five frequencies of interest so that corrections to the data could be made. In addition to utilizing the S/A system, two Pacific Measurements peak power meters (PM-1 and PM-2) were used. PM-1 was used to measure RF power input and PM-2 was used to measure power output. These were used to supply "absolute" power measurements, since the S/A system provides comparison rather than absolute power measurements. Both PM and S/A amplitude data were recorded so that comparisons could be made at a later date. Also due to apparent differences in module RF power outputs as determined from S/A measurements vs PM measurements, the question of accuracies was raised.



Calibration A-B		Calibration C		Calibration A-D	
F_{LL}	50.22 dB	F_{LL}	20.26 dB	F_{LL}	29.54 dB
F_L	50.45 dB	F_L	20.11 dB	F_L	29.51 dB
F_C	49.81 dB	F_C	19.94 dB	F_C	29.57 dB
F_H	49.56 dB	F_H	19.79 dB	F_H	29.52 dB
F_{HH}	49.39 dB	F_{HH}	19.69 dB	F_{HH}	29.48 dB

(U) Fig. 92 — NRL test setup

(U) Some discussion of the measurement accuracies involved in the transmitter RF power measurements is apropos. These accuracies are functions of the measurement tools used and include attenuators (pads), directional couplers, connectors, and electronic measuring instruments of varying complexity. By taking all tolerances into account, the stated accuracies of transmitter measurements could not be greater than approximately ± 1 dB. However, after completion of experiments using three similar peak-reading RF power meters, with two attenuator networks independently calibrated on two HP Automatic Network Analyzers, it was felt that the actual accuracy of power measurements was more nearly ± 0.3 dB.

(U) The investigation of transmitter RF power measurements was sparked by the results of measurements on four modules that indicated lower power outputs than anticipated. These results raised the classic question of whether faults existed in measurement technique or measurement tools, or whether the module transmitter RF power outputs were indeed low. After due investigation, no fault could be found with the measurement technique.

(U) For the HP 8542A Automatic Network Analyzer, when measuring a 50-dB (nominal) pad, the stated verification limit for the analyzer is ± 0.46 dB.* For a particular HP pad (Model 8492A, 50 dB, Serial No. 010) at 1.05 GHz the attenuation is

	-50.24 ± 0.28	dB;
this leaves	± 0.18	dB for system errors;
the verification limit is	-50.24 ± 0.46	dB using this pad.

(U) From these calculations, it would appear that, if this pad is used as a standard for verifying the limits of the HP analyzer, readings between -49.78 dB and -50.70 dB would indicate that the analyzer is within the verification limit. However, it can be seen by the following example that unless the ± 0.18-dB value for system errors is independently verified at the time of calibration, the possible verification limit is extended considerably.

Example:

Assume that the absolute value of the standard pad is exactly

	-49.96 dB	
Assume a system error	- 0.74 dB	for the HP analyzer.
Analyzer reads	-50.70 dB,	the verification limit.

Similarly, if the absolute value of the pad is assumed to be

	-50.52 dB	
and system error is	+ 0.74 dB	
the analyzer reads	-49.78 dB,	also a verification limit.

The verification limit could be ± 0.74 dB, not the stated ± 0.46 dB. We repeat that the example is based on the fact that the stated systems error (± 0.18 dB) is not independently verified during system calibration. (HP does not verify system error independently during field calibrations.)

*"The verification limits shown on the measurement accuracy curves, therefore, reflect both the measurement accuracy of the 8542A system, and the ambiguity of the verification standards," from the Hewlett-Packard publication, "Technical Data, 8542A Automatic Network Analyzer," Mar. 1970.

(U) If a peak reading (PM) RF power meter is used to measure the output of a module through 50 dB of attenuation (needed to obtain 0 dBm assuming a module output of + 50 dBm) the possible errors and accuracies are

± 0.74 dB (50-dB attenuator)
± 0.25 dB (best PM power meter accuracy)
± 0.99 dB (accuracy of measurement)

if operator error is ignored.

(U) Obtained to improve the confidence factor in the measurements were three similar peak-reading RF power meters (PM meters), one average-reading RF power meter (AV meter), and two attenuator setups. One PM meter was used to monitor the input to a module. With each attenuator setup using its own PM meter and the AV meter, measurements of module's output power were made at three frequencies over the band of interest, F_L, F_C, and F_H. The findings are listed in Table 25.

(U) Table 25
Module Output Power vs Frequency

Frequency	Setup 1		Setup 2	
	Peak (W)	Average (W)	Peak (W)	Average (W)
F_L	98.7	93.9	93.9	87.2
F_C	96.3	91.2	92.1	86.7
F_H	85.9	81.7	79.8	75.9

The averages of the F_L, F_C, and F_H readings were taken and tolerances were determined from the maximum readings to average and average to minimum readings. The results were

$$F_L = 93.4\text{W} \begin{matrix} +.24 \text{ dB} \\ -.30 \text{ dB} \end{matrix}$$

$$F_C = 91.6\text{W} \begin{matrix} +.22 \text{ dB} \\ -.24 \text{ dB} \end{matrix}$$

$$F_H = 80.8\text{W} \begin{matrix} +.27 \text{ dB} \\ -.27 \text{ dB} \end{matrix}$$

From these measurements such a high confidence factor was generated that, although the measurement accuracy could be ± 1 dB, it was more likely to be in the order of ± 0.3 dB.

(U) It was, of course, not possible to run a similar series of tests on the S/A system. However, a sample comparison of data taken on MA and Westinghouse transmitters (Table 26) shows good correlation. The conditions under which the data were taken are: zero-degree phase state, 20-dBm input, nominal power supply, room temperature, and center frequency. Corrections to the original data were extracted from the listings in Fig. 92.

(S) Table 26
Sample Comparison, Output Power Corrected

Transmitter Module	Output Power (W)		ORIGINAL DATA (S/A)	
	S/A	PM	(dB)	(dBm)
MA-1	126.8	119.9	-2.4	+0.6
MA-2	100.7	86.9	-3.4	-0.8
W-1	105.4	104.5	-3.2	0.0
W-2	103.0	104.5	-3.3	0.0

Pulsed Measurement System

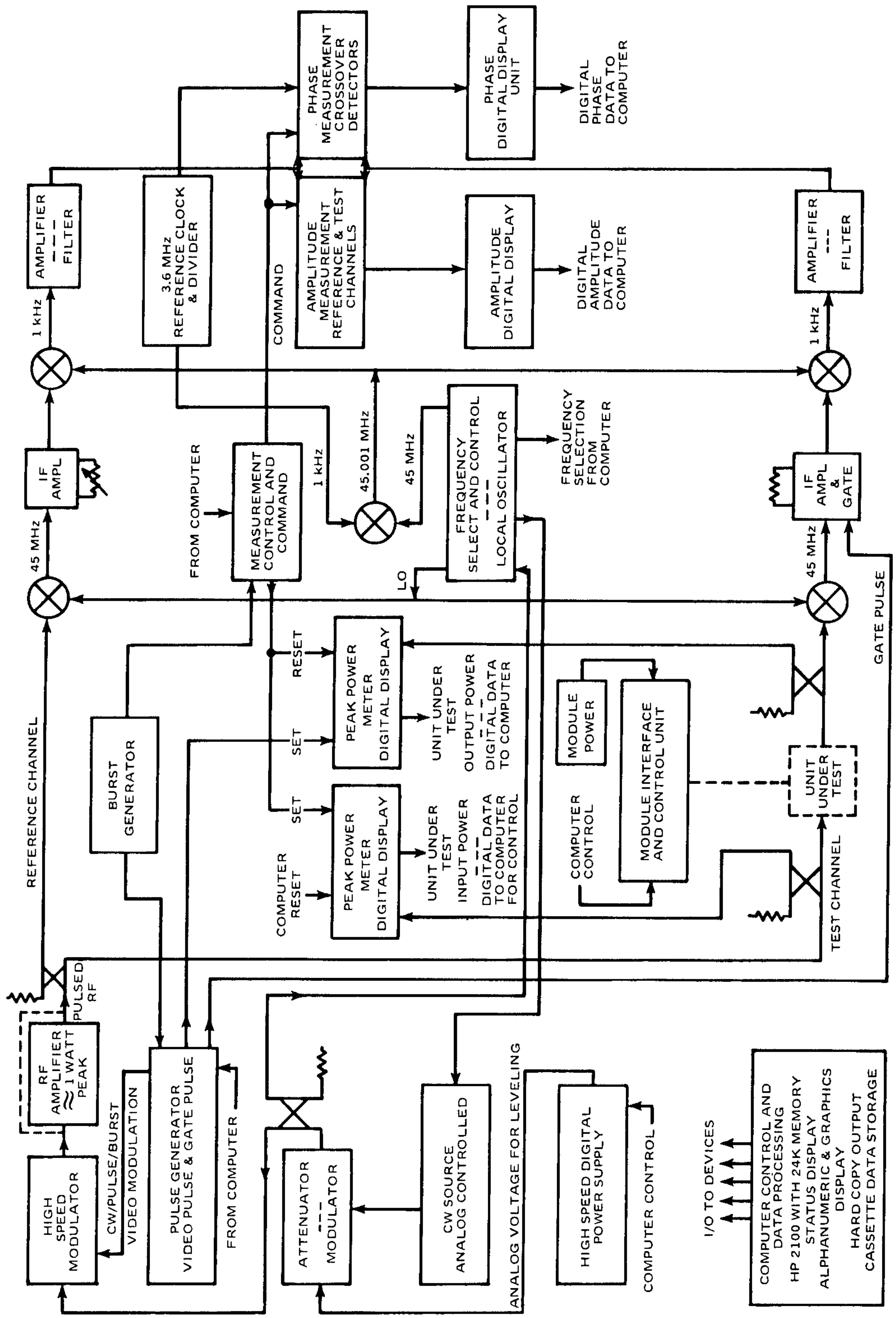
(U) The pulsed measurement system as delivered by Scientific Atlanta and modified at NRL is shown in Fig. 93.

(U) Basically, amplitude and phase are determined by comparison and substitution. Signals are split into two channels, test and reference, and are compared. If the comparison is performed before the unit under test is inserted into the test line and again after insertion, then data are available in the form of system calibration parameters and device-plus-system parameters from which device parameters are easily extracted.

(U) The signal source is combined with two closed-loop systems, which permit rapid measurement with computer control. The first closed-loop system is a frequency loop whereby frequency can be programmed into the loop manually or automatically; the loop makes a continual comparison of the output with the commanded frequency, introducing corrections as required. The system is capable of measuring to 1 kHz and correcting to 10 kHz. The second loop is through the computer and involves measuring output power immediately prior to the unit under test so that RF power leveling at that point can be performed. The power is sampled on an instantaneous basis (approximately 80-nsec window) and the power measurement information is fed to the computer where a comparison with a (previously inserted) desired value is made. A delta results in an error signal which causes an analog voltage to be sent to the signal generator which then corrects power level. Corrections are made to within 0.1 dB of the desired value as read on the peak power meter.

(U) The remainder of the system consists of a receiver and synchronized pulse generator. The receiver is dual channel to accomodate both reference and test signals, and it employs double conversion from RF frequencies to 45 MHz and then to 1 kHz. Comparisons of reference and test signals are performed at 1 kHz, which normally results in a limit on pulsed operation to PRF $\geqq$ 3 kHz. Operation at lower PRFs is possible if the pulse width is approximately 400 μsec or greater and the PRF is such that no PRF lies between 900 and 1000 Hz nor between 1900 and 2000 Hz.

(U) To assure that these criteria are met and to assure accurate conversion between peak and average values requires a pulse generator that is synchronized with the system 1-kHz clocks. In addition the pulse generator produces the video pulse information fed to an



(U) Fig. 93 — Solid State Module Pulsed Microwave Measurement System

RF modulator (the signal source is operated CW) and timing commands for measurement synchronization.

(U) Since the system in essence requires sufficient time to synthesize the 1-Hz signal from the incoming pulse information, the system requires a series of RF pulses for operation and can be viewed as performing an averaging function of phase and amplitude over the pulse and over many pulse samples.

(U) For certain modes of operation above a 3-kHz PRF a sampling window as short as 10 μsec can be moved through the RF pulse making it feasible to acquire data as a function of time. Data, however, are sampled over a series of pulses. It is also possible to place the system in a burst mode where the average duty cycle of the RF signal is kept low while the instantaneous duty cycle is compatible with the ideal 3-kHz or higher PRF.

(U) To complete the system operation, output is available in the form of amplitude in decibels and phase in degrees. This same output is available in BCD format for computer processing. Functions including frequency selection, power leveling, and pulse generator control are computer controllable for automatic operation and are also controllable from the front panels during manual operation. At L-band frequencies (1 to 2 GHz) the system can operate in a high power mode where signal levels up to 150 mW peak are available.

(U) During the transmitter testing described in this report computer control was not available. Frequency was manually programmed into its closed loop and a built-in leveling loop maintained the RF output constant only at the generator. At the unit under test it was necessary to monitor the RF power and manually adjust a variable attenuator to make necessary corrections.

(U) All measurements were made using the burst mode because the normal PRF required to accommodate the modules' 1% duty factor capability would not permit proper operation of the pulsed measurement system.

(U) Data taken on available transmitters are presented in Table 27. These power data are unreduced in terms of watts for various reasons. The primary reason is that by the time the NRL measurements were made on these units, the modules had undergone one or more repairs. The data are not, therefore, directly comparable with those of the contractors. The data are decipherable by examining the method of reduction. For instance, for the S/A output readings,

$$\text{Reference} + \text{Gain} = \text{Reading}$$

$$\text{Gain} = \text{Reading} - \text{Reference}.$$

(U) For W-1, at F_C, with nominal supply voltage,

$$\text{S/A reading} = -3.2 \text{ dB}$$

$$\text{Gain} = -3.2 \text{ dB} - (-33 \text{ dB}) = 29.8 \text{ dB}$$

Input power to module	=	20.0 dBm
Output power (as computed)	=	49.8 dBm
Correction at F_C (from Fig. 92)	=	0.43 dB
Output power (corrected)	=	50.23 dB
	=	105.439 W.

(U) For readings using the Pacific Measurements (PM) power meter,

A 0-dB reading	=	50 dBm

For W-1 at F_C, with nominal supply voltage,

PM reading = 0 dBm	=	50 dBm
Correction	=	0.19 dB
Output power (corrected)	=	50.19 dBm
	=	104.472 W.

(U) Therefore, it can be seen that readings from the S/A system below about -3.5 dB and on the PM meter below about -0.2 dBm indicate power outputs below 100 W. Using this rule of thumb and perusing the W-2 data, we see that this transmitter output is slightly above 100 W at F_C with nominal and low supply voltages and drops off on either side of F_C. At the higher power supply level, its output is below 100 W at all frequencies. This appears to be caused by excessive heating and subsequent detuning (both Westinghouse modules got very hot during transmitter operation). W-1 appeared to operate somewhat more satisfactorily, but its output was always below 100 W at low voltage and the RF input level was 1 dB down. It should be pointed out that both Westinghouse transmitters suffered from pulse breakup and "soft" leading edges of the pulses. This was attributed to a lack of hard-limiting of the Class C output stages because the pulse shapes improved as the input levels were increased.

(U) The MA-1 transmitter performed satisfactorily over the entire specified band with outputs usually well over 100 W under all three conditions of supply voltage and nominal RF input ± 1 dB. The MA-2 transmitter output was below 100 W under most conditions during the final tests. The unit was returned to MA for examination, and a failed output transistor was found.

(U) Both RCA units had been returned to the contractor for repair during the final NRL test period and were unavailable. It should be noted again that these units did operate satisfactorily with respect to power output during preliminary tests.

CONCLUSIONS AND RECOMMENDATIONS

(U) From the tests performed on the six receiver modules, it seems apparent that the contractors were able to meet most of the requirements. The major characteristics of receivers meriting examination are, of course, noise figure, gain, bandwidth, and phase stability.

(U) Table 27
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-1, 20-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-4.3	-1.2	52.7
	22.5	-4.8	-1.2	73.7
	45	-4.9	-1.2	96.4
	90	-4.4	-1.3	137.8
	180	-4.8	-1.2	229.6
	337.5	-4.4	-1.3	17.1
1190	0	-2.3	+ .8	122.9
	22.5	-2.3	+ .8	147.5
	45	-2.4	+ .8	172.3
	90	-2.0	+ .8	218.8
	180	-2.0	+ .8	302.1
	237.5	-1.9	+ .8	102.5
1250	0	-2.4	+ .6	0.9
	22.5	-2.1	+1.3	28.8
	45	-1.9	+1.3	50.4
	90	-2.0	+1.3	95.9
	180	-2.0	+1.3	194.0
	337.5	-2.2	+1.3	2.0
1310	0	-2.5	+ .7	226.7
	22.5	-2.7	+ .9	254.1
	45	-3.0	+ .5	279.3
	90	-2.9	+ .5	332.4
	180	-2.8	+ .5	65.5
	337.5	-2.6	+ .5	245.0
1350	0	-5.1	-1.4	261.9
	22.5	-4.9	-1.4	291.8
	45	-5.1	-1.4	315.6
	90	-5.4	-1.4	8.3
	180	-5.1	-1.5	107.4
	337.5	-5.1	-1.5	290.4

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-1, 19-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-4.8	-1.4	50.0
	22.5	-4.9	-1.4	71.8
	45	-5.1	-1.4	91.8
	90	-5.2	-1.4	138.9
	180	-4.9	-1.4	228.9
	337.5	-4.9	-1.4	11.0
1190	0	-2.6	+ .8	126.4
	22.5	-2.2	+ .8	147.4
	45	-2.4	+ .8	167.3
	90	-2.6	+ .7	212.6
	180	-2.3	+ .7	306.4
	337.5	-2.6	+ .7	109.0
1250	0	-2.4	+1.3	11.2
	22.5	-2.6	+1.2	39.6
	45	-2.6	+1.2	62.0
	90	-2.4	+1.2	110.1
	180	-2.8	+1.2	198.2
	337.5	-2.7	+1.1	10.0
1310	0	-2.7	+ .6	246.6
	22.5	-2.6	+ .5	274.3
	45	-2.6	+ .4	296.1
	90	-3.0	+ .4	346.9
	180	-2.7	+ .4	84.5
	337.5	-2.8	+ .4	263.6
1350	0	-5.5	-1.4	284.2
	22.5	-5.5	-1.6	316.2
	45	-5.4	-1.6	340.3
	90	-5.4	-1.7	30.3
	180	-5.5	-1.7	131.8
	337.5	-5.6	-1.7	314.8

Frequency (Mhz)	Bit (Deg)	Output S/A (db	Output PM (dBm)	Phase S/A (Deg)
MA-1, 21-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-4.7	-1.3	51.9
	22.5	-5.1	-1.4	72.6
	45	-5.2	-1.4	94.8
	90	-5.2	-1.5	140.8
	180	-5.0	-1.5	231.0
	337.5	-4.9	-1.4	15.9
1190	0	-2.6	+ .8	126.0
	22.5	-2.2	+ .7	145.6
	45	-2.4	+ .7	166.3
	90	-2.7	+ .7	211.5
	180	-2.4	+ .7	305.7
	337.5	-2.6	+ .7	107.8
1250	0	-2.3	+1.3	11.5
	22.5	-2.5	+1.2	38.6
	45	-2.5	+1.2	61.6
	90	-2.4	+1.2	109.8
	180	-2.8	+1.2	198.1
	337.5	-2.7	+1.2	11.0
1310	0	-2.6	+ .6	244.4
	22.5	-2.7	+ .5	271.3
	45	-2.6	+ .4	293.9
	90	-3.0	+ .4	343.4
	180	-2.7	+ .4	82.6
	337.5	-2.8	+ .4	262.6
1350	0	-5.5	-1.6	282.7
	22.5	-5.5	-1.6	313.6
	45	-5.4	-1.6	338.1
	90	-5.4	-1.7	27.7
	180	-5.5	-1.7	130.7
	337.5	-5.6	-1.7	314.3

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-1, 20-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-3.7	-1.2	46.2
	22.5	-3.7	-1.2	67.5
	45	-3.7	-1.2	89.8
	90	-3.8	-1.2	136.7
	180	-3.7	-1.2	227.0
	337.5	-3.6	-1.2	11.1
1190	0	- .8	+ .9	124.2
	22.5	- .7	+ .9	143.3
	45	-1.2	+ .9	166.1
	90	-1.0	+ .8	213.9
	180	-0.8	+ .8	311.7
	337.5	-1.1	+ .8	108.9
1250	0	-0.5	+1.4	16.5
	22.5	-0.7	+1.4	44.2
	45	-0.7	+1.4	66.8
	90	-0.7	+1.3	113.0
	180	-1.0	+1.4	209.4
	337.5	-0.7	+1.3	18.0
1310	0	-1.4	+ .8	248.3
	22.5	-1.4	+ .8	275.1
	45	-1.6	+ .7	297.5
	90	-1.9	+ .7	351.6
	180	-1.6	+ .7	85.3
	337.5	-1.5	+ .6	266.1
1350	0	-3.4	-1.2	286.2
	22.5	-3.4	-1.3	317.6
	45	-3.4	-1.3	343.7
	90	-3.6	-1.4	33.5
	180	-3.4	-1.4	132.6
	337.5	-3.6	-1.4	318.9

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-1, 19-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-3.7	-1.1	44.8
	22.5	-3.7	-1.2	66.1
	45	-3.7	-1.2	88.6
	90	-3.8	-1.2	134.6
	180	-3.5	-1.2	226.6
	337.5	-3.6	-1.3	8.2
1190	0	- .7	+1.0	120.3
	22.5	-1.0	+ .9	142.3
	45	-1.1	+ .9	166.0
	90	-1.1	+ .8	214.6
	180	-0.8	+ .8	312.7
	337.5	-1.2	+ .9	106.5
1250	0	-0.5	+1.4	17.1
	22.5	-0.8	+1.4	44.3
	45	-0.7	+1.4	66.8
	90	-0.7	+1.3	112.4
	180	-0.8	+1.3	211.2
	337.5	-0.7	+1.3	17.2
1310	0	-1.3	+ .9	250.1
	22.5	-1.4	+ .7	276.4
	45	-1.4	+ .7	297.9
	90	-1.9	+ .6	352.4
	180	-1.6	+ .7	84.8
	337.5	-1.5	+ .6	265.8
1350	0	-3.0	-1	283.5
	22.5	-3.5	-1.3	320.0
	45	-3.3	-1.3	343.9
	90	-3.6	-1.4	33.7
	180	-3.4	-1.3	133.9
	337.5	-3.6	-1.4	318.0

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-1, 21-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-4.1	-1.4	46.1
	22.5	-4.1	-1.3	66.6
	45	-4.1	-1.3	89.1
	90	-4.1	-1.4	135.4
	180	-4.0	-1.4	227.3
	337.5	-3.7	-1.2	10.6
1190	0	-1.1	+ .8	121.7
	22.5	-1.0	+ .8	140.5
	45	-1.4	+ .8	163.5
	90	-1.3	+ .8	211.4
	180	-1.1	+ .8	311.4
	337.5	-1.3	+ .8	106.1
1250	0	-0.7	+1.4	16.5
	22.5	-0.7	+1.4	42.2
	45	-0.8	+1.4	65.9
	90	-0.7	+1.3	113.0
	180	-1.0	+1.4	211.3
	337.5	-0.6	+1.4	17.6
1310	0	-1.4	+ .8	246.1
	22.5	-1.5	+ .7	272.6
	45	-1.5	+ .7	295.6
	90	-1.9	+ .6	348.5
	180	-1.5	+ .6	83.1
	337.5	-1.5	+ .6	265.0
1350	0	-3.5	-1.2	285.1
	22.5	-3.4	-1.3	316.2
	45	-3.5	-1.3	342.0
	90	-3.6	-1.4	31.0
	180	-3.4	-1.4	131.2
	337.5	-3.6	-1.4	317.2

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-1, 20-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-4.9	-1.4	52.3
	22.5	-5.0	-1.5	74.7
	45	-5.2	-1.5	95.3
	90	-5.3	-1.5	141.5
	180	-4.9	-1.5	231.2
	337.5	-4.9	-1.6	149.0
1190	0	-2.4	+ .7	129.2
	22.5	-2.2	+ .6	149.3
	45	-2.5	+ .5	169.4
	90	-2.7	+ .6	213.9
	180	-2.4	+ .6	307.6
	337.5	-2.6	+ .6	110.1
1250	0	-2.7	+1.1	12.0
	22.5	-2.8	+1.0	40.6
	45	-2.7	+1.0	63.9
	90	-2.6	+1.0	111.1
	180	-2.9	+1.0	199.2
	337.5	-2.8	+1.0	11.3
1310	0	-2.9	+ .4	246.8
	22.5	-2.8	+ .3	274.9
	45	-2.8	+ .2	297.6
	90	-3.2	+ .2	347.7
	180	-2.8	+ .3	85.2
	337.5	-2.9	+ .3	264.7
1350	0	-5.7	-1.8	286.5
	22.5	-5.8	-1.8	318.1
	45	-5.6	-1.9	343.1
	90	-5.7	-1.9	32.3
	180	-5.6	-1.9	133.0
	337.5	-5.8	-1.9	316.2

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-1, 19-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-5	-1.4	50.1
	22.5	-5.1	-1.5	72.1
	45	-5.2	-1.6	92.3
	90	-5.3	-1.5	139.2
	180	-4.9	-1.5	229.0
	337.5	-5.1	-1.7	11.7
1190	0	-2.5	+ .6	130
	22.5	-2.3	+ .6	149.7
	45	-2.5	+ .6	168.0
	90	-2.7	+ .6	213.8
	180	-2.5	+ .6	307.0
	337.5	-2.7	+ .6	108.8
1250	0	-2.8	+1.0	12
	22.5	-2.8	+1.0	39
	45	-2.7	+1.0	62.7
	90	-2.6	+1.0	110
	180	-3.0	+1.0	198.3
	337.5	-2.9	+1.0	9.7
1310	0	-2.9	+ .3	248.0
	22.5	-2.8	+ .3	275.0
	45	-2.8	+ .3	298.6
	90	-3.2	+ .3	347.5
	180	-2.8	+ .3	85.0
	337.5	-2.9	+ .3	264.3
1350	0	-5.8	-1.8	287.6
	22.5	-5.7	-1.8	317.9
	45	-5.6	-1.9	344
	90	-5.6	-1.9	32.6
	180	-5.7	-1.9	133.0
	337.5	-5.8	-1.9	316.2

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-1, 21-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-5.1	-1.5	53.8
	22.5	-5.2	-1.5	74.6
	45	-5.3	-1.5	95.3
	90	-5.3	-1.6	141.6
	180	-5.1	-1.6	232.1
	337.5	-4.8	-1.4	163.0
1190	0	-2.6	+ .6	129.6
	22.5	-2.4	+ .6	149.4
	45	-2.6	+ .5	168.1
	90	-2.8	+ .6	212.2
	180	-2.5	+ .6	306.7
	337.5	-2.7	+ .6	109.0
1250	0	-2.8	+1.1	11.7
	22.5	-2.8	+1.0	39.8
	45	-2.8	+1.0	63.0
	90	-2.6	+1.0	110.2
	180	-3.0	+1.0	198.5
	337.5	-2.9	+1.0	10.5
1310	0	-2.9	+ .3	245.2
	22.5	-2.8	+ .3	273.6
	45	-2.9	+ .2	295.6
	90	-3.2	+ .3	345.4
	180	-2.8	+ .3	84.3
	337.5	-2.9	+ .3	263.6
1350	0	-5.8	-1.8	285
	22.5	-5.7	-1.8	316.9
	45	-5.6	-2.0	341.5
	90	-5.7	-1.9	30.8
	180	-5.6	-1.9	132.2
	337.5	-5.7	-1.9	315.8

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-2, 20-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-7.1	-3.3	16.9
	22.5	-7.0	-3.4	35.2
	45	-6.8	-3.4	55.2
	90	-7.2	-3.4	104.3
	180	-6.9	-3.3	196.1
	337.5	-7.5	-3.8	334.8
1190	0	-4.6	-1.1	102.5
	22.5	-4.6	-1.1	123.5
	45	-4.5	-1.1	144.1
	90	-4.7	-1.1	189.4
	180	-4.7	-1.1	383.0
	337.5	-4.7	-1.1	75.2
1250	0	-3.4	-0.8	340.8
	22.5	-3.5	-0.8	5.8
	45	-3.3	-0.8	29.6
	90	-3.3	-0.8	78.8
	180	-3.8	-0.8	165.8
	337.5	-3.4	-0.8	336.1
1310	0	-4.2	-1.2	231.1
	22.5	-4.2	-1.2	258.2
	45	-4.3	-1.2	280.0
	90	-4.6	-1.2	329.0
	180	-4.3	-1.2	64.5
	337.5	-4.3	-1.2	243.1
1350	0	-5.8	-3.1	265.5
	22.5	-6.0	-3.1	294.7
	45	-6.0	-3.1	320.6
	90	-5.7	-3.1	8.0
	180	-5.7	-3.1	104.7
	337.5	-5.9	-3.2	289.4

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-2, 19-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-8.9	-4.3	199.0
	22.5	-8.6	-4.4	36.4
	45	-8.8	-4.4	58.4
	90	-8.7	-4.3	107.4
	180	-8.3	-4.2	195.9
	337.5	-9.7	-4.9	334.4
1190	0	-4.3	- .8	100.1
	22.5	-4.1	- .7	123.6
	45	-4.1	- .8	144.3
	90	-4.1	- .8	194.8
	180	-4.4	- .8	289.6
	337.5	-3.9	- .8	81.0
1250	0	-3.5	- .7	334.5
	22.5	-3.7	- .7	1.5
	45	-4.0	- .7	26.9
	90	-4.0	- .7	76.2
	180	-4.4	- .7	166.9
	337.5	-3.9	- .7	332.5
1310	0	-5.2	-1	231.6
	22.5	-5.0	-1	258.9
	45	-5.0	-1	283.1
	90	-5.5	-1	334.9
	180	-5.6	-1.1	67.3
	337.5	-5.4	-1.1	248.3
1350	0	-6.9	-3.1	261.8
	22.5	-6.6	-3.2	293.2
	45	-6.8	-3.2	322.5
	90	-6.5	-3.2	8.7
	180	-6.7	-3.3	108.0
	337.5	-6.8	-3.3	294.7

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-2, 21-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-7.7	-3.2	27.3
	22.5	-8.3	-4.0	44.2
	45	-8.2	-4.0	62.4
	90	-8.7	-4.0	110.7
	180	-8.3	-4.0	204.8
	337.5	-8.7	-4.0	345.9
1190	0	-4.4	- .9	99.6
	22.5	-3.9	- .8	128.3
	45	-4.0	- .8	145.8
	90	-4.0	- .8	193.9
	180	-3.8	- .8	228.0
	337.5	-3.6	- .8	84.7
1250	0	-3.8	-0.6	331.0
	22.5	-3.9	-0.7	359.5
	45	-3.9	-0.7	24.5
	90	-4.1	-0.7	75.1
	180	-4.2	-0.8	162.6
	337.5	-3.7	-0.8	332.2
1310	0	-5.0	-0.8	227.9
	22.5	-5.0	-1.0	254.3
	45	-5.2	-1.1	279.5
	90	-5.3	-1.1	328
	180	-5.2	-1.1	65.0
	337.5	-5.2	-1.1	244.6
1350	0	-6.9	-3.1	259.7
	22.5	-6.8	-3.2	290.3
	45	-6.6	-3.3	314.3
	90	-6.5	-3.2	4.1
	180	-6.9	-3.3	104.9
	337.5	-7.1	-3.3	289.8

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-2, 20-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-6.2	-3.8	20.4
	22.5	-6.4	-3.8	39.5
	45	-6.4	-3.8	61.8
	90	-6.3	-3.8	109.7
	180	-6.2	-3.8	200.4
	337.5	-6.5	-4.0	340.4
1190	0	-3.0	- .6	99.2
	22.5	-3.0	- .7	122.1
	45	-2.7	- .7	143.9
	90	-3.2	- .7	193.8
	180	-3.3	- .8	284.7
	337.5	-3.3	- .8	78.2
1250	0	-3.6	- .4	341.6
	22.5	-3.6	- .4	10.1
	45	-3.8	- .4	32.5
	90	-3.8	- .4	84.1
	180	-4.1	- .5	172.6
	337.5	-4.0	- .4	343.4
1310	0	-3.3	- .7	231.5
	22.5	-3.2	- .8	259.7
	45	-3.5	- .8	284.7
	90	3.7	- .8	338.3
	180	-3.2	- .8	70.6
	377.5	-3.3	- .8	250.5
1350	0	-5.5	-2.7	258.6
	22.5	-5.7	-2.8	291.1
	45	-5.7	-2.9	319.5
	90	-5.4	-3.0	8.9
	180	-5.5	-3.0	104.6
	337.5	-5.7	-3.0	290.6

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-2, 19-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-6.3	-4	14.2
	22.5	-6.4	-4	38.0
	45	-6.7	-4.1	57.6
	90	-6.5	-4.0	106.9
	180	-6.1	-3.9	196.8
	337.5	-7.2	-4.5	336.4
1190	0	-2.9	- .6	95.8
	22.5	-3.0	- .7	121.8
	45	-3.2	- .7	143.4
	90	-3.3	- .7	192.3
	180	-3.1	- .8	282.5
	337.5	-3.3	- .8	77.2
1250	0	-3.6	- .4	341.0
	22.5	-3.7	- .4	11.5
	45	-3.7	- .4	35.6
	90	-4.0	- .4	83.8
	180	-4.2	- .4	172.1
	337.5	-4.0	- .4	344.2
1310	0	-3.3	- .7	232.1
	22.5	-3.2	- .8	262.1
	45	-3.3	- .8	285.7
	90	-3.7	- .8	339.3
	180	-3.3	- .8	72.4
	337.5	-3.3	- .8	251.8
1350	0	-5.5	-2.7	259.9
	22.5	-5.7	-2.8	293.6
	45	-5.6	-2.9	320.3
	90	-5.4	-3.0	9.2
	180	-5.4	-3.0	106
	337.5	-5.8	-3.0	292.5

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-2, 21-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-6.3	-3.8	22.9
	22.5	-6.3	-3.8	43.3
	45	-6.5	-3.8	65.0
	90	-6.5	-3.8	112.0
	180	-6.3	-4.0	202.3
	337.5	-6.4	-3.8	342.2
1190	0	-3.0	- .7	99.4
	22.5	-3.1	- .7	121.0
	45	-3.3	- .8	144.1
	90	-3.3	- .8	192.8
	180	-3.3	- .8	284.1
	337.5	-3.2	- .8	79.1
1250	0	-3.7	- .4	341.0
	22.5	-3.7	- .4	7.3
	45	-4.0	- .4	32.5
	90	-3.9	- .4	81.8
	180	-4.1	- .5	169.6
	337.5	-4.0	- .4	341.1
1310	0	-3.3	- .8	229.4
	22.5	-3.2	- .8	256.2
	45	-3.5	- .9	282.5
	90	-3.6	- .8	333.6
	180	-3.3	- .9	68.4
	337.5	-3.3	- .9	248.0
1350	0	-5.6	-2.8	257.5
	22.5	-5.6	-2.8	287.2
	45	-5.8	-3.0	316.9
	90	-5.5	-3.0	3.8
	180	-5.5	-3.0	102.3
	337.5	-5.8	-3.0	288.3

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-2, 20-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-6.3	-4.0	21.8
	22.5	-6.3	-4.2	39.7
	45	-6.5	-4.2	61.8
	90	-6.6	-4.2	109.3
	180	-6.7	-4.1	199.7
	337.5	-7.0	-4.6	337.1
1190	0	-3.1	- .9	102.8
	22.5	-3.1	- .9	122.9
	45	-3.3	-1.0	144.2
	90	-3.5	-1.0	192.2
	180	-3.5	-1.0	283.5
	337.5	-3.6	-1.0	79.0
1250	0	-3.8	- .7	340.5
	22.5	-4.5	- .8	10.9
	45	-4.1	- .8	35.8
	90	-3.9	- .8	84.0
	180	-4.2	- .8	172.9
	337.5	-4.1	- .8	342.3
1310	0	-3.8	-1.1	231.7
	22.5	-3.3	-1.2	261.1
	45	-3.5	-1.2	285.2
	90	-4.0	-1.2	334.6
	180	-3.7	-1.2	70.7
	337.5	-3.7	-1.2	249.2
1350	0	-6.1	-3.2	261.5
	22.5	-5.7	-3.4	288.9
	45	-5.8	-3.4	317.8
	90	-5.8	-3.4	6.3
	180	-5.9	-3.4	105.3
	337.5	-6.1	-3.4	289.6

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-2, 19-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-6.7	-4.5	14.3
	22.5	-6.9	-4.7	36.6
	45	-7.2	-4.8	56.7
	90	-7.0	-4.5	104.5
	180	-6.8	-4.4	194.0
	337.5	-8.0	-5.4	333.1
1190	0	-3.2	- .8	96.6
	22.5	-3.2	-1	120.6
	45	-3.3	-1	140.6
	90	-3.6	- .8	190.0
	180	-3.4	-1.0	279.5
	337.5	-3.6	-1.0	78.3
1250	0	-4.0	- .7	339.6
	22.5	-4.3	- .8	11.1
	45	-4.1	- .8	35.9
	90	-4.0	- .8	84.4
	180	-4.2	- .8	172.1
	337.5	-4.1	- .8	343.0
1310	0	-3.8	-1	232.8
	22.5	-3.5	-1.2	262.5
	45	-3.6	-1.2	286.0
	90	-4.0	-1.2	336.3
	180	-3.7	-1.2	71.6
	337.5	-3.7	-1.2	250.2
1350	0	-6.1	-3.2	262.5
	22.5	-5.8	-3.4	291.5
	45	-5.9	-3.4	319.1
	90	-5.8	-3.4	7.8
	180	-5.9	-3.5	106.1
	337.5	-6.1	-3.5	290.4

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
MA-2, 21-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-6.3	-4	25.4
	22.5	-6.4	-4	44.6
	45	-6.5	-4	65.3
	90	-6.6	-4	111.5
	180	-6.5	-4	202.6
	337.5	-6.7	-4.2	340.5
1190	0	-3.2	- .9	103.6
	22.5	-3.1	- .9	124.6
	45	-3.4	-1.0	146.2
	90	-3.6	-1.0	192.2
	180	-3.5	-1.0	284.7
	337.5	-3.6	-1.0	79.7
1250	0	-3.9	- .8	341.1
	22.5	-3.8	- .8	7.3
	45	-4.1	- .8	34.3
	90	-4.0	- .8	82.9
	180	-4.1	- .8	169.9
	337.5	-4.1	- .8	341.3
1310	0	-3.8	-1.2	230.4
	22.5	-3.8	-1.1	256.1
	45	-3.6	-1.2	283.1
	90	-3.9	-1.2	331.4
	180	-3.7	-1.3	68.0
	337.5	-3.7	-1.2	246.9
1350	0	-6.2	-3.3	260.6
	22.5	-6.2	-3.3	289.7
	45	-5.9	-3.4	317.7
	90	-5.7	-3.4	3.9
	180	-6.0	-3.5	103.0
	337.5	-6.1	-3.5	286.8

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-1, 20-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-4.7	-2.2	72.2
	22.5	-4.9	-2.3	95.4
	45	-5.0	-2.3	119.8
	90	-5.0	-2.3	159.8
	180	-4.8	-2.4	242.3
	337.5	-4.7	-2.4	41.0
1190	0	-4.9	-1.0	172.1
	22.5	-4.7	-1.0	194.1
	45	-4.7	-1.0	220.4
	90	-4.3	-1.0	268.1
	180	-3.9	-1.0	1.4
	337.5	-4.9	-1.1	153.0
1250	0	-3.2	-0	185.1
	22.5	-3.0	0	209.7
	45	-2.9	0	235.2
	90	-2.7	0	277.6
	180	-3.0	0	5.5
	337.5	-3.3	0	181
1310	0	-4.8	-1.6	86.2
	22.5	-4.8	-1.6	110.6
	45	-4.8	-1.6	136.6
	90	-5.3	-1.8	179.9
	180	-4.8	-1.5	287.4
	337.5	-4.8	-1.6	97.3
1350	0	Below range		
	22.5			
	45			
	90			
	180			
	337.5			

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-1, 19-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-5.5	-3	245.4
	22.5	-5.5	-3	264.2
	45	-5.2	-2.3	301.7
	90	-5.2	-2.3	348.5
	180	-5.3	-2.4	75.9
	337.5	-4.9	-2.3	233.9
1190	0	-4.0	-0.7	352.7
	22.5	-4.3	-0.7	10.8
	45	-3.7	-0.7	44.2
	90	-3.8	-0.7	89.2
	180	-4.9	-0.7	170.8
	337.5	-3.4	-0.8	345.5
1250	0	-4.9	-1.9	299.8
	22.5	-4.9	-1.8	322.1
	45	-4.9	-1.6	349.2
	90	-5.1	-1.7	38.3
	180	-4.9	-1.8	135.8
	337.5	-4.8	-1.8	299.4
1310	0	-4.2	-1.0	266.2
	22.5	-4.2	-1.0	288.0
	45	-4.2	-1.0	312.2
	90	-4.6	-1.1	355.9
	180	-4.1	-1.0	108.3
	337.5	-4.3	-1.1	278.2
1350	0	-14.0	-10.7	314.4
	22.5	-15.1	-11.7	336.3
	45	-13.3	-10.0	2.6
	90	-20.5	-17.0	47.9
	180	-15.7	-12.4	161.1
	337.5	-15.9	-12.0	337.4

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-1, 21-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-4.7	-2.0	278.1
	22.5	-4.8	-2.1	298.6
	45	-5.1	-2.1	327.6
	90	-4.9	-2.2	12.7
	180	-5.0	-2.2	105.2
	337.5	-4.7	-2.2	253.6
1190	0	-3.4	-0.6	14.3
	22.5	-3.6	-0.6	33.5
	45	-3.7	-0.7	59.0
	90	-3.5	-0.7	106.8
	180	-3.5	-0.7	198.8
	337.5	-3.5	-0.7	358.2
1250	0	-3.6	-0.3	324.5
	22.5	-3.7	-0.4	347.8
	45	-3.8	-0.4	16.3
	90	-4.0	-0.4	67.1
	180	-4.0	-0.4	162.8
	337.5	-3.6	-0.4	324.9
1310	0	-4.1	-1.0	282.4
	22.5	-4.1	-1.0	304.5
	45	-4.4	-1.0	328.4
	90	-4.5	-1.0	19.5
	180	-4.2	-1.0	123.1
	337.5	-4.1	-1.0	295.8
1350	0	-6.6	-3.3	337.0
	22.5	-6.6	-3.4	358.6
	45	-6.4	-3.3	23.1
	90	-7.3	-3.7	70.0
	180	-6.6	-3.4	182.2
	337.5	-6.5	-3.4	0.5

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-1, 20-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-4.4	-2.0	280.7
	22.5	-4.5	-2.0	300.4
	45	-4.8	-2.1	329.4
	90	-4.2	-2.1	15.0
	180	-4.7	-2.1	104.8
	337.5	-4.3	-2.1	255.6
1190	0	-2.5	-.6	11.3
	22.5	-2.8	-.6	33.9
	45	-2.7	-.6	62.3
	90	-2.1	-.7	105.8
	180	-2.7	-.7	201.9
	337.5	-2.3	-.7	356.2
1250	0	-3.2	-0.2	320.4
	22.5	-3.3	-0.2	342.5
	45	-3.5	-0.2	10.3
	90	-3.7	-0.2	60.0
	180	-3.8	-0.2	161.4
	337.5	-3.2	-0.3	319.1
1310	0	-3.6	-0.8	279.5
	22.5	-3.9	-0.8	302.4
	45	-4.1	-0.8	326.7
	90	-4.0	-0.8	17.3
	180	-3.8	-0.8	120.4
	337.5	-3.8	-0.8	293.1
1350	0	-6.8	-3.8	331.4
	22.5	-6.6	-3.8	355.3
	45	-6.5	-3.5	21.1
	90	-7.9	-4.6	65.9
	180	-7.2	-4.1	174.0
	337.5	-6.8	-3.8	356.4

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W1, 19-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-4.9	-2.4	286.5
	22.5	-5.0	-2.4	305.9
	45	-5.1	-2.4	337.5
	90	-4.5	-2.4	20.2
	180	-4.8	-2.4	110.8
	337.5	-4.5	-2.4	259.7
1190	0	-2.8	-0.9	18.9
	22.5	-3.1	-0.9	40.8
	45	-2.8	-0.9	69.1
	90	-2.4	-0.9	112.0
	180	-2.9	-0.9	207.0
	337.5	-2.6	-0.9	1.8
1250	0	-3.6	-0.5	313.7
	22.5	-3.7	-0.5	336.6
	45	-3.8	-0.4	4.1
	90	-4.0	-0.4	53.9
	180	-4.2	-0.4	155.6
	337.5	-3.6	-0.5	314.3
1310	0	-3.7	-1.0	275.3
	22.5	-4.0	-1.0	296.2
	45	-4.2	-0.9	321.1
	90	-4.3	-1.0	9.5
	180	-3.9	-0.9	114.6
	337.5	-3.8	-1.0	286.2
1350	0	-7.8	-4.8	330.2
	22.5	-8.0	-5.1	352.2
	45	-7.9	-4.7	17.9
	90	-11.2	-7.5	60.4
	180	-9.1	-5.8	171.0
	337.5	-7.9	-4.8	354.7

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-1, 21-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-4.9	-2.5	295.9
	22.5	-5.1	-2.5	316.4
	45	-5.0	-2.5	343.5
	90	-4.5	-2.5	25.7
	180	-4.8	-2.4	119.4
	337.5	-4.7	-2.5	265.7
1190	0	-3.0	-0.9	22.0
	22.5	-3.0	-0.9	45.9
	45	-2.7	-1.0	71.2
	90	-2.5	-1.0	115.1
	180	-2.9	-1.0	213.3
	337.5	-2.8	-1.0	4.6
1250	0	-3.4	-0.4	332.0
	22.5	-3.5	-0.4	354.4
	45	-3.6	-0.4	21.8
	90	-4.1	-0.4	73.5
	180	-3.7	-0.4	175.7
	337.5	-3.5	-0.4	330.5
1310	0	-3.8	-1.0	284.5
	22.5	-4.0	-1.0	307.1
	45	-4.3	-1.0	331.1
	90	-4.3	-1.0	22.1
	180	-4.0	-1.0	124.5
	337.5	-4.0	-1.0	298.4
1350	0	-5.7	-2.7	348.4
	22.5	-5.6	-2.7	10.7
	45	-5.7	-2.7	34.9
	90	-6.5	-3.0	80.7
	180	-6.0	-2.8	189.5
	337.5	-5.7	-2.8	11.9

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-1, 20-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-4.8	-2.5	277.6
	22.5	-5.1	-2.5	295.9
	45	-5.2	-2.5	325.5
	90	-4.9	-2.5	12.6
	180	-5.1	-2.5	101.6
	337.5	-4.7	-2.5	251.9
1190	0	-3.2	-1.0	5.8
	22.5	-3.2	-1	28.6
	45	-3.0	-1	58.5
	90	-2.6	-1	105.0
	180	-2.8	-1	196.9
	337.5	-2.9	-1	348.2
1250	0	-3.9	-0.8	306.5
	22.5	-3.9	-0.8	327.7
	45	-4.0	-0.7	354.8
	90	-4.4	-0.8	44.0
	180	-4.8	-0.8	147.0
	337.5	-3.9	-0.9	304.8
1310	0	-3.8	-1.3	275.2
	22.5	-4.0	-1.2	297.4
	45	-4.2	-1.2	321.4
	90	-4.5	-1.3	12.2
	180	-4.1	-1.2	117.4
	337.5	-4.0	-1.3	288.7
1350	0	-8.7	-5.2	328.9
	22.5	-8.5	-5.1	352.2
	45	-8.7	-5.4	16.2
	90	-11.0	-7.1	60.2
	180	-9.2	-5.8	170.0
	337.5	-8.6	-5.2	354.3

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-1, 19-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-5.0	-2.6	261.4
	22.5	-5.3	-2.8	279.7
	45	-5.2	-2.5	315.2
	90	-5.1	-2.6	1.7
	180	-5.4	-2.6	87.9
	337.5	-4.7	-2.6	240.9
1190	0	-3.5	-1.0	353.7
	22.5	-3.8	-1.0	13.7
	45	-3.2	-0.9	47.7
	90	-2.8	-1.0	94.2
	180	-3.4	-0.9	178.5
	337.5	-3.0	-1.0	339.2
1250	0	-4.7	-2.1	297.0
	22.5	-4.6	-1.9	318.2
	45	-4.6	-1.6	344.5
	90	-5.0	-1.9	33.4
	180	-5.5	-1.9	136.1
	337.5	-4.5	-2.0	296.3
1310	0	-3.9	-1.4	264.9
	22.5	-4.0	-1.4	285.7
	45	-4.0	-1.4	307.9
	90	-4.7	-1.4	356.1
	180	-4.1	-1.3	107.3
	337.5	-4.0	-1.4	276.8
1350	0	-13.4	-10.1	314.8
	22.5	-13.8	-10.4	337.4
	45	-12.7	-8.9	3.9
	90	-21.6	-17.6	52.7
	180	-15.6	-12.2	160.0
	337.5	-14	-10.6	340.2

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-1, 21-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-4.4	-2.2	273.8
	22.5	-4.7	-2.3	293.2
	45	-4.8	-2.2	320.5
	90	-4.8	-2.3	8.7
	180	-4.8	-2.4	100.6
	337.5	-4.4	-2.3	249.3
1190	0	-3.2	-0.8	5.7
	22.5	-3.2	-0.8	28.3
	45	-3.0	-0.8	56.5
	90	-2.5	-0.8	103.1
	180	-2.8	-0.9	197.3
	337.5	-3.0	-0.9	347.1
1250	0	-3.3	-0.4	312.1
	22.5	-3.5	-0.4	334.2
	45	-3.5	-0.4	0.9
	90	-3.8	-0.4	50.7
	180	-4.2	-0.5	153.3
	337.5	-3.3	-0.5	310.6
1310	0	-3.8	-1.2	279.3
	22.5	-3.9	-1.2	301.7
	45	-4.3	-1.2	325.7
	90	-4.3	-1.2	16.1
	180	-3.9	-1.2	118.6
	337.5	-3.8	-1.2	292.1
1350	0	-7.5	-4.1	330.7
	22.5	-7.4	-4.0	353.4
	45	-7.4	-4.1	18.4
	90	-8.4	-4.7	65.0
	180	-7.6	-4.4	173.5
	337.5	-7.2	-4.0	358.1

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-2, 20-dBm Input, V-nom, S/A Ref -33 Db				
1150	0	-4.8	-2.2	72.5
	22.5	-5.0	-2.2	94.1
	45	-5.1	-2.2	120.8
	90	-5.1	-2.3	161.7
	180	-4.8	-2.3	244.9
	337.5	-4.8	-2.3	40.4
1190	0	-4.4	-1.0	176.1
	22.5	-4.6	-1.0	197.3
	45	-4.6	-1.0	221.7
	90	-4.6	-1.0	267.5
	180	-4.4	-1.0	358.0
	337.5	-4.3	-1.0	155.2
1250	0	-3.3	0	187.6
	22.5	-3.1	0	211.4
	45	-2.9	0	236.5
	90	-2.9	0	279.1
	180	-3.2	0	9.4
	337.5	-3.3	0	183.3
1310	0	-4.7	-1.5	87.4
	22.5	-4.8	-1.4	112.2
	45	-4.9	-1.4	138.9
	90	-5.1	-1.6	183.2
	180	-4.7	-1.4	288.1
	337.5	-4.8	-1.5	98.1
1350	0	Below range		
	22.5			
	45			
	90			
	180			
	337.5			

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-2, 19-dB Input, V-nom, S/A Ref -33 dB				
1150	0	-5.1	-2.5	86.9
	22.5	-5.1	-2.5	108.3
	45	-5.2	-2.5	134.3
	90	-5.2	-2.5	172.7
	180	-4.9	-2.5	254.7
	337.5	-4.9	-2.5	55.1
1190	0	-4.8	-1.4	186.7
	22.5	-4.8	-1.3	209.8
	45	-4.4	-1.3	234.8
	90	-4.4	-1.4	282.0
	180	-4.1	-1.4	13.1
	337.5	-4.7	-1.4	166.0
1250	0	-3.6	-0.2	188.1
	22.5	-3.4	-0.2	213.3
	45	-3.2	-0.2	239.6
	90	-3.0	-0.2	281.3
	180	-3.3	-0.2	10.5
	337.5	-3.6	-0.2	183.6
1310	0	-5.9	-2.8	82.5
	22.5	-5.8	-2.6	107.4
	45	-5.8	-2.5	132.6
	90	-6.6	-3.1	174.8
	180	-5.6	-2.4	284.5
	337.5	-5.9	-2.7	92.8
1350	0	Below Range		
	22.5			
	45			
	90			
	180			
	337.5			

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-2, 21-dBm Input, V-nom, S/A Ref -33 dB				
1150	0	-5.1	-2.4	91.7
	22.5	-5.2	-2.4	112.7
	45	-5.2	-2.4	135.9
	90	-5.1	-2.4	176.5
	180	-4.9	-2.4	259.9
	337.5	-4.9	-2.4	56.1
1190	0	-4.6	-1.2	174.8
	22.5	-4.6	-1.1	196.7
	45	-4.7	-1.1	223.0
	90	-4.4	-1.2	269.9
	180	-4.0	-1.2	3.2
	337.5	-4.7	-1.2	155.3
1250	0	-3.4	0	185.1
	22.5	-3.2	0	209.3
	45	-3.0	0	235.3
	90	-2.8	0	278.2
	180	-3.1	0	5.6
	337.5	-3.3	0	180.5
1310	0	-4.5	-1.4	91.2
	22.5	-4.6	-1.4	116
	45	-4.7	-1.4	141.4
	90	-4.9	-1.5	186.9
	180	-4.6	-1.4	291.8
	337.5	-4.6	-1.4	102.6
1350	0	Below Range		
	22.5			
	45			
	90			
	180			
	337.5			

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-2, 20-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-4.9	-2.7	76.1
	22.5	-4.9	-2.7	98.9
	45	-4.9	-2.7	124.7
	90	-4.8	-2.8	164.9
	180	-4.5	-2.8	246.5
	337.5	-4.7	-2.7	41.5
1190	0	-4.5	-1.3	171.4
	22.5	-4.6	-1.3	194.7
	45	-4.4	-1.3	220.0
	90	-3.7	-1.2	268.5
	180	-3.3	-1.2	357.4
	337.5	-4.3	-1.2	153.0
1250	0	-3.4	-0.2	189.2
	22.5	-2.9	-0.2	214.4
	45	-2.7	-0.2	239.8
	90	-2.8	-0.2	281.4
	180	-3.2	-0.2	8.7
	337.5	-3.4	-0.2	186.1
1310	0	-5.1	-2.4	86.5
	22.5	-5.2	-2.4	111.0
	45	-5.4	-2.4	137.0
	90	-5.8	-2.7	180.6
	180	-5.0	-2.3	287.8
	337.5	-5.1	-2.4	98.0
1350	0	Below Range		
	22.5			
	45			
	90			
	180			
	337.5			

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-2, 19-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-4.3	-2.5	72.9
	22.5	-4.4	-2.5	94.7
	45	-4.5	-2.5	122.1
	90	-4.4	-2.6	162.0
	180	-3.9	-2.6	242.6
	337.5	-4.1	-2.6	38.6
1190	0	-4.6	-1.2	177.3
	22.5	-4.7	-1.2	200.7
	45	-4.1	-1.2	227.1
	90	-3.6	-1.2	270.1
	180	-3.0	-1.2	359.1
	337.5	-4.9	-1.3	155.6
1250	0	-3.6	0	176.1
	22.5	-3.2	0	202.0
	45	-2.8	0	228.8
	90	-2.7	0	269.3
	180	-3.0	0	355.4
	337.5	-3.5	-0.1	172.9
1310	0	-5.5	-2.9	75.8
	22.5	-5.6	-2.9	99.4
	45	-5.7	-2.6	125.8
	90	-6.6	-2.6	167.4
	180	-5.0	-2.4	277.9
	337.5	-5.8	-3.0	85.1
1350	0	Below Range		
	22.5			
	45			
	90			
	180			
	337.5			

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-2, 21-dBm Input, V-low, S/A Ref -33 dB				
1150	0	-4.6	-2.8	86.8
	22.5	-4.6	-2.4	109.0
	45	-4.5	-2.4	134.4
	90	-4.4	-2.4	173.9
	180	-4.2	-2.4	256.3
	337.5	-4.6	-2.4	51.4
1190	0	-4.2	-1.2	170.5
	22.5	-4.4	-1.2	193.0
	45	-4.2	-1.2	218.6
	90	-3.9	-1.2	263.4
	180	-3.5	-1.3	353.3
	337.5	-4.3	-1.3	148.2
1250	0	-3.4	-0.2	189.1
	22.5	-3.1	-0.2	213.0
	45	-2.8	-0.2	238.8
	90	-2.8	-0.2	281.9
	180	-3.3	-0.2	8.8
	337.5	-3.5	-0.2	184.6
1310	0	-4.8	-2.1	91.6
	22.5	-5.0	-2.0	117.2
	45	-5.1	-2.1	142.1
	90	-5.3	-2.2	188.2
	180	-4.9	-2.1	291.4
	337.5	-4.9	-2.1	102.9
1350	0	Below Range		
	22.5			
	45			
	90			
	180			
	337.5			

(U) Table 27 (Cont'd)
NRL Transmitter Data

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-2, 20-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-8.0	-2.7	85.1
	22.5	-7.9	-2.7	106.6
	45	-8.0	-2.7	130.2
	90	-7.7	-2.7	171.0
	180	-8.0	-2.7	246.0
	337.5	-7.9	-2.7	49.0
1190	0	-7.5	-1.3	173.5
	22.5	-7.5	-1.3	197.1
	45	-7.5	-1.3	222.7
	90	-6.8	-1.3	264.7
	180	-6.8	-1.3	354.1
	337.5	-7.7	-1.4	150.2
1250	0	-5.8	0	187.1
	22.5	-5.7	0	210.5
	45	-5.6	0	236.2
	90	-5.7	0	276.5
	180	-6.4	0	1.7
	337.5	-6.0	0	182.8
1310	0	-6.8	-1.3	88.2
	22.5	-6.9	-1.4	112.2
	45	-7.1	-1.3	136.0
	90	-7.3	-1.4	181.6
	180	-7.1	-1.2	287.8
	337.5	-6.8	-1.3	98.2
1350	0	Below Range		
	22.5			
	45			
	90			
	180			
	337.5			

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-2, 19-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-7.8	-2.6	78.8
	22.5	-8.0	-2.6	101.6
	45	-7.9	-2.6	125.6
	90	-7.8	-2.7	165.8
	180	-7.8	-2.7	237.4
	337.5	-7.8	-2.7	43.1
1190	0	-6.5	-1.3	183.8
	22.5	-6.8	-1.3	205.2
	45	-7.1	-1.3	226.7
	90	-7.1	-1.3	275.8
	180	-7.0	-1.3	1.2
	337.5	-6.1	-1.3	163.1
1250	0	-6.0	0.0	185.2
	22.5	-5.8	0	211.9
	45	-5.7	0	235.8
	90	-5.7	0	276.6
	180	-6.6	0	6.8
	337.5	-6.1	0	179.5
1310	0	-7.1	-1.8	78.7
	22.5	-7.1	-1.7	103.1
	45	-7.2	-1.6	128.0
	90	-8.2	-2.2	166.1
	180	-7.2	-1.5	282.3
	337.5	-7.2	-1.8	89.4
1350	0	Below range		
	22.5			
	45			
	90			
	180			
	337.5			

Frequency (MHz)	Bit (Deg)	Output S/A (dB)	Output PM (dBm)	Phase S/A (Deg)
W-2, 21-dBm Input, V-high, S/A Ref -33 dB				
1150	0	-7.8	-2.7	85.0
	22.5	-8.0	-2.7	108.4
	45.0	-8.0	-2.8	130.7
	90	-7.9	-2.7	170.9
	180	-7.9	-2.8	251.8
	337.5	-7.7	-2.7	48.2
1190	0	-7.3	-1.3	168.9
	22.5	-7.5	-1.3	195.5
	45	-7.3	-1.3	217.7
	90	-6.9	-1.3	262.8
	180	-7.2	-1.3	343.7
	337.5	-7.3	-1.3	146.0
1250	0	-5.9	0	185.3
	22.5	-5.8	0	209.8
	45	-5.7	0	236.7
	90	-5.6	0	278.1
	180	-6.5	0	7.9
	337.5	-5.9	0	181.1
1310	0	-6.5	-1.1	90.5
	22.5	-6.6	-1.1	115.0
	45	-6.7	-1.1	138.9
	90	-7.0	-1.2	183.2
	180	-7.1	-1.1	292.2
	337.5	-6.7	-1.1	101.8
1350	0	Below Range		
	22.5			
	45			
	90			
	180			
	337.5			

(U) With respect to noise figure, it is evident that the low noise amplifiers in the receivers did, indeed, meet the requirements adequately. It is unfortunate that protective circuitry and circulators, particularly the latter, are required for typical applications of the receivers. Those items degrade the noise figure considerably.

(U) The receiver gains in all cases were more than adequate to meet requirements. The meeting of the 1-dB bandwidth requirement poses a somewhat different problem. This, of course, is the matter of specification interpretation which is normally governed by a specific system requirement. In many cases receivers perform satisfactorily during all phase states for a given supply voltage. In operation it would be reasonable to assume that a dedicated power source would be furnished. This would usually mean that, using wiring rules consonant with good engineering practice, all receivers at any given time would be operating from substantially identical supply power levels. A change in the prime voltage source would then affect all receivers in like manner.

(U) The differential phase characteristic of all receivers was quite good and met most requirements adequately. Insertion phase lengths as denoted by the electrical equivalent lengths showed unit-to-unit constancy for each contractor. It is not known, of course, whether the same constancy could be maintained during production runs. This is particularly the case for discontinuous production runs and production runs made at different points in time. Some phase-equalizing adjustment might be necessary during installation.

(U) Of some concern are the reliabilities of the modules. Numerous failures occurred under storage and testing conditions. These were variously attributed to the high sulfur content of the air in the vicinity of the module locations, or to some manufacturing inadequacy, or to unprotected components, and in some cases were simply not explained. In most cases, repair was graciously performed by the contractor.

(U) It must be remembered, too, that these were engineering models, hand assembled and possibly repaired or modified before delivery to NRL. The use of the modules at NRL as display units (show-and-tell) did not enhance their protection since for such "operation" cover plates were removed to allow examination of case interiors. (These units, as stated previously, were delivered in unsealed cases.)

(U) The location of the modules in a test area high in sulfur-containing air points up the need for passivating or otherwise protecting components and/or the possible need for hermetically sealed units filled with dry nitrogen or other inert gas. It is expected that the final units to be delivered will meet these requirements; all contractors are aware of the need for corrective action to be taken before the delivery of any subsequent units.

(U) The testing of receivers in the linear portions of their characteristics was not always done by the contractors, although it was by NRL. Some of the problems associated with testing automatically at the proper RF power levels are related to the test equipments involved. These delivered fixed output levels which were designed for testing passive RF components, but were not suitable for testing multistage amplifiers which could overload in their final output stages. It is expected that future receivers will be tested at appropriate RF signal levels.

(U) The test results obtained by contractors RCA, MA, and Westinghouse are presented in Tables 28, 29, and 30. The results shown were from data taken prior to shipping the engineering models to NRL. Subsequent module failures and repairs before and during tests at NRL render valid comparisons with NRL data impossible, so these tables are provided for reference only. It is felt that the tests performed at NRL do give a fair evaluation of the receivers, even though the testing was not as thorough as those of the contractors. It is expected that the Phase II final versions of the modules will be more completely examined by NRL so that the attributes and problem areas of the modules are well exposed and properly evaluated.

(U) The results of the NRL receiver investigation make it difficult to choose the best from among the contractors. Each receiver had both good and bad scores in some respects. The clearest example might be the Westinghouse W-2 receiver. This unit had constant gain independent of supply voltage variations and was the only unit to meet the bandwidth specification. However, its VSWR characteristic was noticeably poor, particularly when compared with the other receivers.

(U) Although the NRL investigation has been described as "limited," it should be pointed out that it is probably one of the most thorough performed to date on solid state transmitter/receiver modules. Over 1200 pages of computer-generated data (printouts) pertinent to the six module receivers were produced. It was evident that only summaries and a few examples of other data could be presented here. The most meaningful and illustrative data sheets were selected from the mass in order to demonstrate the salient features, both good and bad, of the units tested. These were supplemented with results of bench tests as required to round out the picture of the receivers' capabilities.

(U) The six transmitters suffered from the same lack of reliability as the receivers. Again, failures were sometimes attributed to the high sulfur content of the air in the vicinity. In addition, however, the transistors used in the final amplifiers were multicellular. The cells are individual transistor units that are paralleled on the substrate chip. As many as 32 cells were on some of these chips. As with other first generation devices, failures were not uncommon as device manufacturers went through their own learning processes and attempted to solve problems of failure mechanisms and other causes of malfunctions. It is expected that later devices will gradually exhibit higher reliabilities.

(U) The engineering model transmitters performed remarkably well for first units. In most cases desired output powers were achieved over much if not all of the specified bandwidth. Phase response was not always to specification. Phase response of a device is a parameter that varies with temperature, voltage, and external tuned circuits as well as internal tuned circuits. Hard limiting in Class C amplifiers and good heat sinks within and external to the device help to stabilize phase. The problems associated with phase are expected to diminish as device manufacturing techniques and module assembly techniques improve.

(S) Table 28
RCA Test Results*

Parameter	Specification	RCA-1 Performance	RCA-2 Performance
1. Frequency (midband)	1250 MHz	1250 MHZ	1250 MHz
2. Bandwidth (1 dB)	±5% Frequency agile; 20-MHz instantaneous signal	10%	10%
3. DC supply voltage	±2% Provided, minimize required voltage	30 V ±2% 10 V ±2% 2.5 V ±2%	30 V ±2% 10 V ±2% 2.5 V ±5%
4. Power output (min)	100 W peak	>100 W from -30°C to + 70°C	>100 W peak from -30°C to + 70°C
5. Pulse length	100 μsec max	100 μsec	100 μsec
6. RF power input	100 mW or less	80 mW ±1 dB	80 mW ±1 dB
7. Duty cycle (max)	1% fixed	1%	1%
8. RF interference	30 dB below the transmit output power level	>30 dB below transmit signal	>30 dB below transmit signal
9. Antenna port (load VSWR)	Must survive a 5:1 VSWR	No change in output operating into 5:1 VSWR	No change in output operating into 5:1 VSWR
10. Receiver (noise figure)	4.0 dB max	<3.9 dB	<3.9 dB
11. Overall module (efficiency)	Worst case: 23% Nominal: 25% Design goal: 27%	>25% from -30°C to + 70°C	-22.9% from -30°C + 70°C
12. Transmitter (efficiency η_t)	Worst case: 37% Nominal: 43% Design goal: 45%	>27%	>25% from -30°C + 70°C
13. Transmitter gain	30 dB min	>30.0 dB	>30.0 dB

* From Ref. 1.

(S) Table 28 (Continued)
RCA Test Results

Parameter	Specification	RCA-1 Performance	RCA-2 Performance
14. Spurious intra-pulse transmitter noise	-35 dB max	>50 dB below output signal	>50 dB below output signal
15. Spurious oscillation	-50 dB max	>50 dB below output signal	>50 dB below output signal
16. RF amplitude	5.0% max for 100-μsec pulse length	<1.2%	<1.2%
17. Transmit phase sensitivity DC voltages	1° max cumulative phase change	<1.7 degrees	<2.14 degrees
18. Harmonic	50 dB below 100 W	Second harmonic >45 dB at 1187 MHz >47 dB at 1250 MHz >35 dB at 1313 MHz Higher harmonics >60 dB	Second harmonic >35 dB at 1187 MHz >38 dB at 1250 MHz >40 dB at 1313 MHz Higher Harmonics >50 dB
19. Transmit phase settling	±5 degrees within 50 nsec after 10% to 90% rise time	<8.5 degrees	<11.5 degrees
20. Transmitter/receiver isolation	⩾35 dB	Transmit mode >31 dB Receive mode >45 dB	Transmit mode >32.5 dB Receive mode >42 dB
21. Reverse isolation	⩾35 dB under varying antenna load VSWR	>19 dB	>19 dB
22. Amplifier rise time (10% to 90%)	⩽50 nsec	<40 nsec	<50 nsec
23. Phase stability to temperature	1 degree/C max	Transmit mode <0.5 degree/°C Receive mode <1.0 degree/°C	Transmit mode <0.5 degree/°C Receive mode <1.0 degree/°C
24. Receiver gain	25 dB min	>28 dB at -30°C >26 dB at 25°C >26.4 dB at 70°C	>26.2 dB at -30°C >28 dB at 25°C >26 dB at 70°C

(S) Table 28 (Continued)
RCA Test Results

Parameters	Specification	RCA-1 Performance	RCA-2 Performance
25. Dynamic range of receiver	1-dB compression, -25 dBm module input	1-dB compression with input >-25 dBm	1-dB compression with input >-25 dBm
26. Transmit phase insensitivity input power	±5 degrees for ±1-dB change in RF drive	<5.3 degrees	<5.7 degrees
27. Receiver phase sensitivity to voltage	0.5 degrees max cumulative phase change	<4.5 degrees	<4.7 degrees
28. Input receiver VSWR	<1.4:1 at antenna input port	<1.4:1	<1.4:1
29. Logic and T/R levels	10-V COS/MOS compatible logic	10-V COS/MOS logic	10-V COS/MOS logic
30. Phase shifter logic/input	Provision to sum two serial 4-bit inputs	Two serial 4-bit inputs	Two serial 4-bit inputs
31. Phase shifter bits	4 bits, 180, 90, 45, 22.5 degrees	4 bits, 180, 90, 45, and 22.5 degrees	4 bits, 180, 90, 45, and 22.5 degrees
32. Differential module phase-shift accuracy	±10 degree peak and 5 degrees rms	rms error <3 degrees peak error <8 degrees	rms error <3 degrees peak error <8 degrees
33. Insertion phase	To be established	Transmit mode 5340.4 degrees Receive mode 2224.8 degrees	Transmit mode 5320.7 degrees Receive mode 2225.0 degrees
34. Phase shifter logic load time	20 μsec max	<13 μsec	<13 μsec
35. Phase shifter settling time	0.5 μsec max	<0.5 μsec	<1.5 μsec
36. TR switching time	5 μsec max	<5 μsec	<5.2 μsec

(S) Table 28 (Continued)
RCA Test Results

Parameter	Specification	RCA-1 Performance	RCA-2 Performance
37. Clock speed max	160 kHz; ±5%	200 kHz	200 kHz
38. Manifold port VSWR	⩽1.5:1	<1.6:1	⩽1.5:1
39. Intrapulse phase linearity	1° peak max	Transmit mode <4.0 degrees Receive mode <0.5 degrees	Transmit mode <5.0 degrees Receive mode <0.5 degrees
40. Intrapulse amplitude linearity	0.5 dB max	Transmit mode <0.2 dB Receive mode <0.2 dB	Transmit mode <0.25 dB Receive mode <0.2 dB
41. Pulse-to-pulse phase and amplitude variations	Phase variation ⩽1 degree peak amplitude variation ⩽0.2-dB peak	<1 degree peak <0.2 dB peak	<1 degree peak <0.2 dB peak
42. Phase tracking between modules	12 degrees rms, 17 degrees peak	<12 degrees rms 17 degree peak	Transmit mode <13 degree rms; 40 degree peak Receive mode <2 degrees rms; 5 degrees peak
43. Transmitter P_{out} and receiver gain tracking	1.0 dB rms		Transmit mode <1.0 dB rms Receive mode <1.0 dB rms
44. Quadratic phase error	⩽15 degrees		
Temperature	Operable: - 30°C to +70°C		
Thermal	Peak junction temperature ⩽144°C		

(U) Table 29
Performance Achievement Summary: MA Test Results*

Item	Description	EM-1	EM-2	Remarks
1.	Midband frequency	Y	Y	
2.	1-dB bandwidth	Y*	Y*	
3.	DC power supply voltages	Y	Y	
4.	Power output (min)	Y	Y	
5.	Pulse length	Y	Y	
6.	RF power input	Y	Y	
7.	Duty cycle	Y	Y	
8.	RF interference	Y	Y	
9.	Antenna port load VSWR	Y	Y	
10.	Receiver noise figure	Y*	Y*	Degraded 0.5-0.59 dB at elevated temperature
11.	Overall module efficiency	25%	27%	35% (respecified 27%) (Addenda I of technical proposal)
12.	Transmitter efficiency	29%	33%	40% (respecified 34%) (Addenda I of technical proposal)
13.	Transmitter gain	Y	Y	
14.	Spurious intrapulse transmitter noise	-50	-50	-35
15.	Spurious oscillation	-50	-50	-50
16.	RF output amplitude droop during transmitter pulse	6%	6%	5%
17.	Transmit phase sensitivity to changes in DC supply voltages	3.27%	2.1%	1%
18.	Harmonic content of transmitter output	-53	-53	-50
19.	Phase settling of transmitter output	Not measured	Not measured	
20.	Transmitter/receiver isolation	53/58	82/86	35
21.	Antenna port and transmitter output (TX mode)	Y	Y	
22.	Amplifier rise time	40	40	50

*From Ref. 2.
*Y = MET SPECIFICATION

(U) Table 29 (Continued)
Performance Achievement Summary: MA Test Results

Item	Description	EM-1	EM-2	Remarks
23.	Phase stability to temperature	0.6/0.6	0.6/0.8	1
24.	Receiver gain	Y	Y	25
25.	Dynamic range of receiver	Y	Y	
26.	Transmitter phase sensitivity to RF power input	+1.7 -0.9	+2.0 -1.5	±5
27.	Receiver phase sensitivity to changes in DC supply voltages	0.4	0.25	0.5
28.	Antenna port VSWR	<1.2:1	1.33:1	1.4:1
29.	Logic and T/R levels	4.6	4.6	5.0
30.	Phase shifter logic/inputs	Translation only	Translation only	
31.	Phase shifter bits nominal at $F_C \pm F_H - F_L / F_C$	Y	Y	
32.	Differential module phase shift accuracy	5 degrees peak	6 degrees peak	± 10 degrees peak
33.	Insertion phase length	---	---	
34.	Phase shifter logic load time	OK	OK	
35.	Phase shifter settling time	Not measured	Not measured	
36.	TR switching time	OK	OK	
37.	Clock speed (max)	OK	OK	
38.	Manifold port VSWR	No	No	1.5:1
39.	Transmit or receive intrapulse phase linearity	4/<0.1	6/<0.1	1 degree
40.	Transmit or receive intrapulse amplitude linearity	OK	OK	
41.	Pulse-to-pulse phase and amplitude variations	OK	OK	
42.	Transmitter and receiver phase tracking	?/3.3 degrees	?/3.3 degrees	17 degrees peak
43.	Transmitter (power output) and receiver gain tracking	0.4/0.3	0.4/0.3	1.0
44.	Quadratic phase error in transmit or receive	Not measured	Not measured	15 degrees

(S) Table 30
Westinghouse Test Results*

Parameter	Specification	W-1 1187 MHz	W-1 1250 MHz	W-1 1312 MHz	W-2 1187 MHz	W-2 1250 MHz	W-2 1312 MHz
Power output	100 W peak (min)	108 W	130 W	104 W	105 W	140 W	106 W
Transmitter efficiency	40% (min)	18%	26%	32%	19%	30%	36%
Overall module efficiency	35% (min)	15%	21%	25%	16%	24%	26%
Transmitter gain	30 dB (min)	30 dB minimum (all)					
Receiver noise figure	4.0 dB (max)	3.3 dB maximum (all)					
Receiver gain	25 dB (min)	26.7 dB	26.9	27.0	26.8	26.6	26.4
Receiver dynamic range	1 dB compression at - 25 dBm	- 21 dBm	- 18	- 18	- 25	- 21	- 19
Transmit/receive isolation	35 dB (min)	> 35 dB (all)					
Manifold port VSWR	1.5:1 (max)	1.9:1	1.5:1	1.1:1	1.8:1	1.6:1	1.2:1
Antenna port VSWR	1.4:1 (max)	1.1:1	1.2:1	1.1:1	1.3:1	1.2:1	1.35:1
Differential phase shift	± 10 degrees peak 5 degrees rms	<±10 degrees peak (all)					
Phase shifter logic load time	8 μsec (max)	8 μsec (all)					
Phase shifter settling time	1.5 μsec (max)	<0.5 μsec (all)					
T/R switching time	5 μsec T-R max R-T	6 μsec (W-1); 1 μsec			9 μsec (W-2)		
Transmit phase settling	50 nsec (max)	50 nsec (W-1)			50 nsec (W-2)		
Transmit rise time	50 nsec (max)	50 nsec (all)					

*From Ref. 3.

(S) Table 30 (Continued)
Westinghouse Test Results

Parameter	Specification	W-1 1187 MHz	W-1 1250 MHz	W-1 1312 MHz	W-2 1187 MHz	W-2 1250 MHz	W-2 1312 MHz
RF interference	30 dB	← 30 dB →					
Spurious oscillation	- 50 dB (max)	← - 50 dB →					
Spurious intrapulse	- 35 dB (max)	← - 50 dB →					
Transmit amplitude droop	5.0% (max)	← 3.5% →			← 3.9% →		
Transmit phase sensitivity to DC voltage	1 degree/V max	← 0.25 degree →			← 0.2 degree →		
Transmit harmonics	- 50 dB (min)	← - 48 dB →			← - 48 dB →		
Transmit phase sensitivity to input power	±5 degrees/±1 dB (max)	← ±3.5 degrees →			← ±4 degrees →		
Intrapulse phase linearity	1 degree peak (max)	← 11 degrees peak →			← 9 degrees peak →		
Intrapulse amplitude linearity	0.5 dB max	← 0.5 dB max →			← 0.7 dB max →		
Pulse-to-pulse phase variation	1 degree peak (max)	← 0.3 degree peak →			← 0.5 degree peak →		
Pulse-to-pulse amplitude variation	0.2 dB peak	← 0.24 dB peak →			← 0.23 dB peak →		

(S) To summarize, it is felt that the objective of Phase I of this program was achieved. Indeed, six operating solid state L-band T/R modules were successfully produced by three contractors. As far as the key requirements are concerned, reliability is in need of considerable improvement; long operating life will follow once reliability is increased; the space environment compatibility can be had by component passivation and/or hermetically sealing the modules; small size, low weight were achieved; reproducibility at moderate cost will be a function of quantity production coupled with good manufacturing and quality control techniques.

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REFERENCES

1. "Solid-State Transmit Receive Module Final Report," RCA, Missile and Surface Radar Division, Moorestown, N.J. (Secret Report, Unclassified Title), Feb. 9, 1973.

2. H. Balshem, J.N. Jansen, J.E. Miley, R. Munro, G. Simpson, and R.F. Wade, "Final Engineering Report, Contract Number N00014-72-C-0213," Microwave Associates, Inc., Burlington, Mass., Feb. 1973.

3. "Final Report, Solid State Transmit/Receive Module," Westinghouse Defense and Electronic Systems Center, Baltimore, Md. (Secret Report, Unclassified Title), June 1973.

Appendix A
NRL SPECIFICATION FOR TRANSMIT/RECEIVE MODULES

(S) The module must meet the following specifications:

Electrical Specifications for L-Band T/R Module

Parameter	Specification
(1) Frequency (midband)	1.25 GHz
(2) Bandwidth (1 dB)	± 5% Frequency agile; 20 MHz instantaneous signal.
(3) DC Supply Voltage	Internal regulation and protection to be designated by contractor; however, the number of different potentials must be minimized along with their magnitudes. Internal energy supplies and/or regulators must be provided to meet the electrical requirements specified herein. In addition, a sufficiently rapid fail-safe mode of operation must be achievable with the module so as to permit adjacent modules (connected to common outside DC buses) to continue to operate without degraded performance. Prime voltage supply buses outside the module are expected to be regulated ± 2% maximum.
(4) Power Output (min)	100 W peak at antenna port including circuit, network, circulator, isolator, and connector losses
(5) Pulse Length	20 μsec min; 100 μsec max (no pulse bursts)
(6) RF Power Input	100 mW or less, sufficient to maintain transmitter saturation at output with ± 1 dB variation in input level while meeting phase requirements specified herein.
(7) Duty Cycle (max)	1% fixed
(8) RF Interference	RF energy generated within the module and appearing on any power supply or logic lead to the transceiver module shall be at least 30 dB below the transmit output power level.

Parameter	Specification
(9) Antenna Port Load VSWR	50 ohm nominal, however module must survive a 5:1 VSWR, on an intermittent basis, while operating in either mode without damage. Unless otherwise noted, all performance specifications contained herein are based on a nominal 50-ohm antenna load.
(10) Receiver Noise Figure	4.0 dB max
(11) Overall Module Efficiency	35%; Goal = 40%
(12) Transmitter Efficiency (η_t)	40%; Goal = 45% including all circuit network transmission line isolator-circulator and connector losses, where $\eta_t = \dfrac{\text{Average } RF_{out}}{\text{Av } DC_{in} + \text{Av } RF_{in}}$.
(13) Transmitter Gain	30 dB
(14) Spurious Intrapulse Transmitter Noise within signal band with RF drive present.	-35 dB maximum compared to module peak power output
(15) Spurious oscillation during pulse within any 0.5-MHz bandwidth from 0.5 to 2.0 GHz (transmitter)	-50-dB maximum compared to module peak power output
(16) Allowable RF output amplitude droop during pulse (transmitter)	5.0% maximum at 1% duty cycle for 100-μsec pulse length
(17) Allowable transmit phase sensitivity to changes in DC supply voltages	1-degree maximum cumulative output signal phase change
(18) Harmonic on transmit	The harmonic and out-of-band spurious outputs shall be down at least 50 dB from the 100-W transmitter output
(19) Phase settling on transmit	The output phase shall settle to within 5 degrees of nominal in less than 50 nsec after 10% to 90% rise time of amplifier.

Parameter	Specification
(20) Transmitter/Receiver Isolation	Sufficient isolation will be provided within the module so as to suppress regeneration between the transmitter and receiver independent of the mode of operation. In addition (for purposes of possible calibration) the reverse isolation between the antenna port and the RF input to the module shall be at least 35 dB down when transmitter/receiver switches are in transmit mode. When in receive mode, the reverse isolation between the RF input to the module and the antenna load port shall be 35 dB min.
(21) Reverse isolation between antenna port and transmitter final amplifier output in transmit mode	Sufficient to prevent degradation of amplifier output power and/or reliability $\geqq$ 35 dB under varying antenna load VSWR created by beam steering.
(22) Amplifier rise time (10% to 90%)	$\leq$ 50 nsec
(23) Phase stability to temperature	1 degree/°C maximum (transmit or receive)
(24) Receiver gain	25-dB minimum (antenna port to manifold port)
(25) Dynamic range of receiver	1-dB compression at the output with -25 dBm maximum measured at input to module
(26) Transmitter phase sensitivity per RF input power	+5 degrees for 1-dB change in RF drive level
(27) Allowable receiver phase sensitivity to changes in DC supply voltages	0.5 degrees maximum cumulative receiver output signal phase change
(28) Input receiver VSWR relative to 50 ohm	1.4:1 at antenna input port of circulator/isolator relative to 50 ohms when module is in receive mode
(29) Logic and T/R levels	Standard 5-V TTL-compatible logic shall be used in the module to drive the phase shifter and the TR switches.

Parameter	Specification
(30) Phase Shifter Logic inputs	Provisions must be made in module to sum two serial 4-bit inputs and store in an accumulator register. Provisions will be made to transfer accumulator data into a driver storage register upon command by a transfer pulse.
(31) Phase shifter bits nominal at 1.25 GHz ± 5% frequency	Four bits, 180, 90, 45, and 22.5 degrees
(32) Differential module phase shift accuracy for any combination of bits and when connected to matched source or load (depending on whether in transmit or receive mode) in the manifold	± 10 degrees peak and 5 degrees rms overall module error as measured for a line length phase shifter which has an increasing linear phase with increase in frequency
(33) Insertion phase	During Phase I, the contractor shall establish the absolute electrical length or insertion phase of the module in both modes of operation and make necessary provision for adjustments in production in order to eliminate wave length ambiguities, while at the same time meeting both the absolute and relative phase specifications and allowable deviation from linearity.
(34) Phase shifter logic load time	1.5 μsec maximum
(35) Phase shifter settling time	0.5 μsec maximum from start of transfer pulse to settled phase shifter
(36) TR switching time	5 μsec maximum
(37) Clock speed max.	2.5 MHz ± 5%
(38) Manifold port VSWR	$\leqq$ 1.5:1
(39) Transmit or receive intrapulse phase linearity	1 degree peak max over specified instantaneous signal bandwidth located anywhere within agile band, with a change rate not exceeding 0.5degree/10 MHz
(40) Transmit or receive intrapulse amplitude linearity	0.5 dB max over specified instantaneous signal bandwidth located anywhere within agile band

Parameter	Specification
(41) Pulse-to-pulse phase and amplitude variations	For any successive quantity of six (6) 100-μsec pulses, repeated at 1% duty cycle and operating over a 20-MHz instantaneous signal bandwidth, located at any fixed reference within the agile bandwidth, periodic phase variation about the mean shall not exceed 1 degree peak. Under the same condition, amplitude variation about the mean pulse amplitude shall not exceed 0.2 dB peak. A periodic variation is defined as having a sinusoidal form (including a damped sinusoid) of at least two full cycles.
(42) Transmitter and receiver phase tracking between modules over any 20 MHz within the 1-dB bandwidth	12 degrees rms*; 17 degrees peak
(43) Transmitter P_{out} and receiver gain tracking between modules over any 20 MHz within the 1-dB bandwidth	1.0 dB rms*

*RMS tracking for subsequent production quantities is defined as follows: For shippable quantities less than the total lot procurement, the mean and standard deviation will be calculated by the contractor for all modules heretofore produced, and the subject group to be shipped will fall within the limits specified.

Appendix B
NOISE TEMPERATURE/NOISE FIGURE DERIVATION*

(U) The effective input noise temperature T_e is a measure of the noise contributed by the amplifier irrespective of the temperature of the source. For an amplifier with no spurious response, the effective input noise temperature can be related to the noise figure F by using the equation

$$T_e = (F - 1)\ 290\ K,$$

where F is the noise figure expressed as a power ratio.

When measured with the AIL Type 70 Hot-Cold Body Standard Noise Generator, the Y-factor is obtained from

$$Y = \frac{T_2 + T_e}{T_1 + T_e},$$

where $T_2 = 373.1$ K and $T_1 = 77.3$ K.

The effective input noise temperature of the amplifier is, therefore,

$$T_e = \frac{T_2 - T_1}{Y - 1} - T_1 = \frac{295.9\ K}{Y - 1} - 77.3\ K.$$

The noise figure is

$$F = 1 + \frac{T_e}{290} = 0.734 + \frac{1.02}{Y - 1}$$

$$N.F. = 10 \log_{10} \left(0.734 + \frac{1.02}{Y - 1}\right)$$

*From AIL instruction book on the Type 70 Hot-Cold Body Standard Noise Generator (slightly modified) published by Airborne Instruments Laboratory, Deerpark, N.Y.